

8. CONTRIBUTIONS FROM COASTAL CLIFF EROSION TO THE LITTORAL BUDGET

Coastal rivers, streams, and bluffs are the dominant sources of littoral material for California's beaches. As the construction of shoreline structures to protect eroding cliffs and bluffs has intensified in recent years, concern has developed regarding the significance of this armor in reducing the supply of sand to the beaches from the naturally eroding bluffs. In order to quantify this reduction, it is necessary to assess the extent of coastal bluffs and cliffs along the length of the coast of California, the significance of bluff erosion in producing beach sand, and the degree to which armor or other bluff protection has reduced this input. Littoral cell budgets determined to date suggest that in California, ~70-90% of the littoral sand is provided by rivers and streams (Bowen and Inman, 1966; California Coastal Commission, 1974; Best and Griggs, 1991a, b; Knur and Kim, 1999). Because the California coastline consists of a series of essentially self-contained littoral cells, however, it is necessary to evaluate the sand budgets of individual littoral cells to determine how important bluff erosion and, therefore, bluff armoring are to each cell.

8.1 The Geologic and Tectonic Setting of the California Coast

The geology of California and other states on the west coast of the United States is strikingly different from the geology found on east or Gulf coasts. Even a casual visitor to the coastline can observe the obvious differences between the coastal mountains and sea cliffs that characterize much of California's coastal zone and the broad, low-relief coastal plain, sand dunes and barrier islands of New Jersey or North Carolina. The Atlantic and Pacific coasts of North America have had very different geologic histories, and, as a result, are characterized by very different landforms that raise different issues for human occupancy.

California is on the leading edge of a large tectonic plate (the North American Plate) that has been colliding with the Pacific Plate to the west for millions of years. This collision and the subsequent plate interaction have produced California's unique and dynamic landscape. The diverse features such as the Sierra Nevada, the San Andreas fault and its associated earthquakes, the rugged coastal mountains of Mendocino and Big Sur, as well as the uplifted marine terraces and coastal cliffs that characterize much of California's coast all have their origins in millions of years of large scale tectonic processes that continue today.

Large-scale coastal landforms such as the coastal mountains, uplifted terraces, and sea cliffs also have been shaped by surface processes such as waves, rainfall and runoff, and landslides or other mass movements. In addition, sea level along the coast has changed constantly throughout geologic time in response to changing global climate and tectonic activity (Figure 8.1). As a result, the present position of the shoreline is only a temporary one. While the changes are not rapid, the evidence is clear that sea level has been rising for the past 18,000 years. Scientific

consensus indicates that it will continue to rise in the foreseeable future, though the rate of rise and the maximum elevation that will be reached are uncertain. This should raise serious concerns about our increasingly intensive development of the shoreline, not just in California, but worldwide.

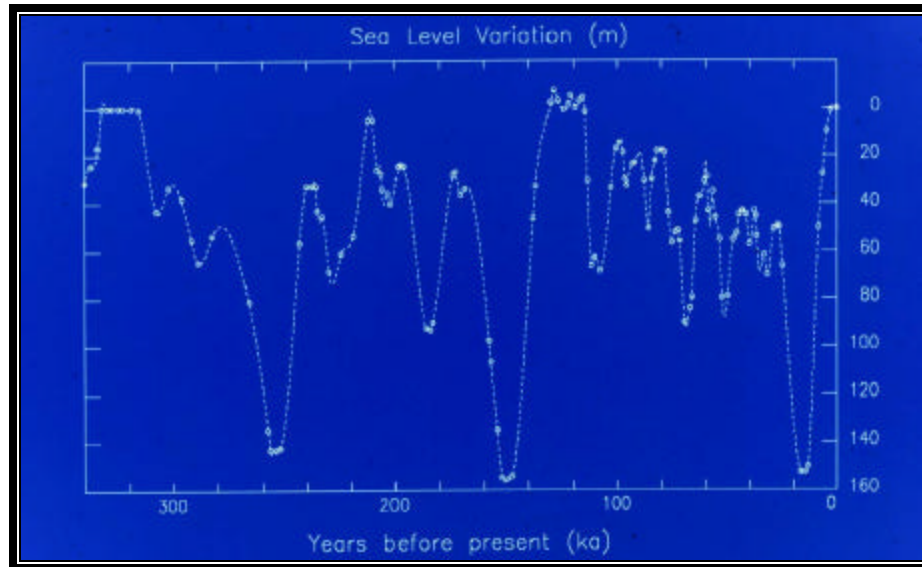


Figure 8.1 Sea level rise curve for the past 340,000 years (Lajoie, 1986)

Eighteen thousand years ago, the climate was considerably cooler than it is now and the earth was in the waning stages of a period of glaciation. Approximately 11 million cubic miles (45 million cubic kilometers) of seawater were locked up on the continents as ice caps and glaciers, which covered large areas of the earth. The removal of this seawater from the oceans led to a worldwide drop in sea level of about 430 feet (130 m). The shoreline along the coast of California at that time was five to fifteen miles offshore from its current position. As the climate warmed, the ice caps began to melt and the glaciers retreated. This melt water flowed into the ocean and sea level rose globally at an average rate of nearly 0.4 inches (1 cm) a year until about 5000 years ago. From about 5000 years ago until the present, the rate has slowed, although sea level has continued to rise at about .08 inches/year (2 mm/year) for the past century (National Research Council, 1987). There are convincing data and arguments that the present rate of sea level rise will continue and in all likelihood increase in the century ahead.

The rise in sea level that accompanied the period of global warming and ice melting that began 18,000 years ago flooded the continental shelves surrounding the continents. Along the coast of California, the shoreline progressed 5 to 15 miles (8 to 25 km) landward, with waves eroding and leveling the landscape and forming sea cliffs as the sea advanced. Throughout the period of major sea level rise (18,000 to 5,000 years ago), most of the coastline of California retreated at average rates of 2 to 6 feet (0.6 to 1.8 m) annually (based on the average width of the continental shelf and the time required for sea level to transgress the shelf). As sea level rise slowed, the

erosion rate declined and began to approach the average rates of sea cliff retreat we witness today ranging from a few inches to 1 foot/year (30 cm/yr) in most places in the state (Griggs and Savoy, 1985).

8.2 Sea Cliffs and Sea Cliff Erosion

Results from this study show that the great majority (72%) of the coast of California consists of actively eroding sea cliffs. Earlier studies (USACOE, 1971) indicated that about 950 miles (1520 km), or 86%, of California's coast are eroding based on a large-scale regional analysis. Practically speaking, the entire coast of California has been retreating or eroding for the past 18,000 years. There is an important distinction, however, between the erosion or retreat of coastal cliffs or bluffs, which is an irreversible unidirectional process, and the seasonal or longer term erosion of the beaches, which can be recoverable. Thus, even as the coastline continues to retreat landward, beaches will be present as long as the supply of sand to the shoreline is maintained. When the shoreline of California was 10 miles (16 km) to the west, there were beaches on the outer edge of the continental shelf. As sea level rose and the shoreline moved eastward, the beaches migrated with the shoreline because sand continued to be provided by rivers, streams and cliff erosion. So, while the entire shoreline of California continues to slowly migrate landward and the cliffs and bluffs physically erode, the beaches migrate as well, but they are not necessarily eroding or narrowing. There are locations, however, particularly in Southern California, where the beaches are believed to be narrowing or eroding due to reduction of sand supplies; to date, however, this has not been comprehensively or quantitatively evaluated.

While the overall long-term statewide rate of coastal migration is a function of the rate of sea level rise, there are significant local or regional differences in erosion rates. These rates vary as a function of both the resistance to erosion of the materials making up the cliffs and the physical forces acting to wear away the cliffs (Benumof and Griggs, 1999; Benumof et. al., 2000). The hardness, or degree of consolidation of the cliff rock, and the presence of internal weaknesses such as joints or faults, all directly affect the resistance of the material to both slope failure and wave action. The wave energy reaching any particular stretch of cliffs, the presence or absence of a protective beach, the tidal range or sea level fluctuation, the climate, including rainfall, runoff, and the frequency of El Niño events or damaging storms, as well as groundwater flow, all influence the rate and scale of sea cliff retreat.

Sections of coast consisting of unweathered crystalline rock, such as the granite of the Monterey Peninsula, usually erode at imperceptibly slow rates, at least during the period of historic photographs. At some locations on the Monterey Peninsula, virtually no change was detected between photos taken over a 60 to 70 year span (Griggs and Savoy, 1985). Within these generally resistant areas, however, erosion rates can vary considerably. Wave attack over time

can cause the weaker zones, such as the fractures and joints, to form inlets and coves. The more resistant rock is left behind as points, headlands and sea stacks.

In striking contrast to the slow erosion of hard rocks, erosion can be far more rapid (over 1 foot (30 cm) per year, on average) where the bluffs consist of weaker sedimentary rocks such as shale, siltstone, sandstone, or unconsolidated materials such as dune sand or marine terrace deposits (Plate 81). In these areas, which are characteristic of much of Humboldt, Santa Barbara, Santa Cruz, and San Diego counties, the cliffs often retreat in a more linear fashion, producing relatively straight coastlines. Lithologic, stratigraphic and structural weaknesses or differences are the key factors affecting erosion rates in sedimentary rocks. Cliff erosion is due not only to waves undercutting the base of the cliff, but also to rockfalls, landsliding and slumping higher on the cliff face, often as a result of weakening due to groundwater percolation. The orientation and spacing of joints in the sandstones, siltstones, and mudstones that make up the cliffs surrounding northern Monterey Bay are the dominant factors affecting cliff retreat in this area (Griggs and Johnson, 1979).



Plate 8.1 Erodible bluffs consisting of unconsolidated marine terrace deposits and soil in San Mateo County.

Cliff failure during strong seismic shaking represents a significant but little appreciated coastal hazard, primarily due to the infrequent nature of large earthquakes. The potential for earthquakes that can affect coastal bluffs is high along the entire length of the state's coastline (Plate 8.2; Griggs and Scholar, 1997). No part of the coastline of California is more than 15 miles (24 km) from an active fault (Jennings, 1975), and many areas are considerably closer.



Plate 8.2 Seismically-induced bluff failure in Daly City, 1989

8.2.1 Erosion Rates

It is important to understand exactly what is meant by *average annual erosion rate*. Geologists normally measure the amount of coastal retreat or erosion over the time interval spanned by available aerial photographs or historic maps, and divide this distance by the number of years of record to get an average annual rate. However, years of observation, particularly during severe winters such as the El Niño years of 1982-83 and 1997-98, have shown that erosion in California is usually episodic and irregular. Although the “average” rate of erosion along a particular stretch of sea cliffs may be determined as one foot/year (30 cm/year), erosion may occur as large five to ten foot wide blocks failing instantaneously every 10 to 15 years (Plate 8.3), rather than in even, one foot annual increments. Now that we have a better understanding of longer-term climatic periods and the impact of El Niño events on the coastline, short-term records and erosion data (i.e. less than 25 or 30 years) should be used with caution, as they may not represent long-term patterns.



Plate 8.3 Episodic coastal bluff failure in Capitola.

8.2.2 The Eroding Coast of California: Historical Perceptions

A 1971 Corps of Engineers regional inventory of the California coastline classified only 14.2% of the coast as *non-eroding* while 7% (76.4 miles, or 123 km) were classified as *critical erosion* (defined as areas where structures and/or utilities were threatened), with the remainder designated as *non-critical erosion* (U.S. Army Corps of Engineers, 1971). A subsequent investigation by the California Department of Navigation and Ocean Development (Habel and Armstrong, 1977) defined the erosion problem somewhat differently. Approximately 99.4 miles (160 km, or 9%) of the coast were delineated as eroding with existing development threatened, and an additional 480 miles (772.5 km; 27.3%) were classified as eroding at a rate fast enough that future development would eventually be threatened. Thus, a total of 335.5 miles (540 km; 36.3%) of the California coastline were considered threatened due to high erosion rates.

The most recent inventory of hazardous coastal environments expands the scale of the problem areas further. In 1985, sixteen coastal geologists participated in the preparation of a statewide inventory of coastline conditions, classifying 310.7 miles (500 km; 28.6%) as *high risk*, and an additional 405 miles (650km; 36.8%) as requiring *caution* (Griggs and Savoy, 1985). These data indicate that two-thirds of the California coastline is subject to a significant coastal erosion hazard.

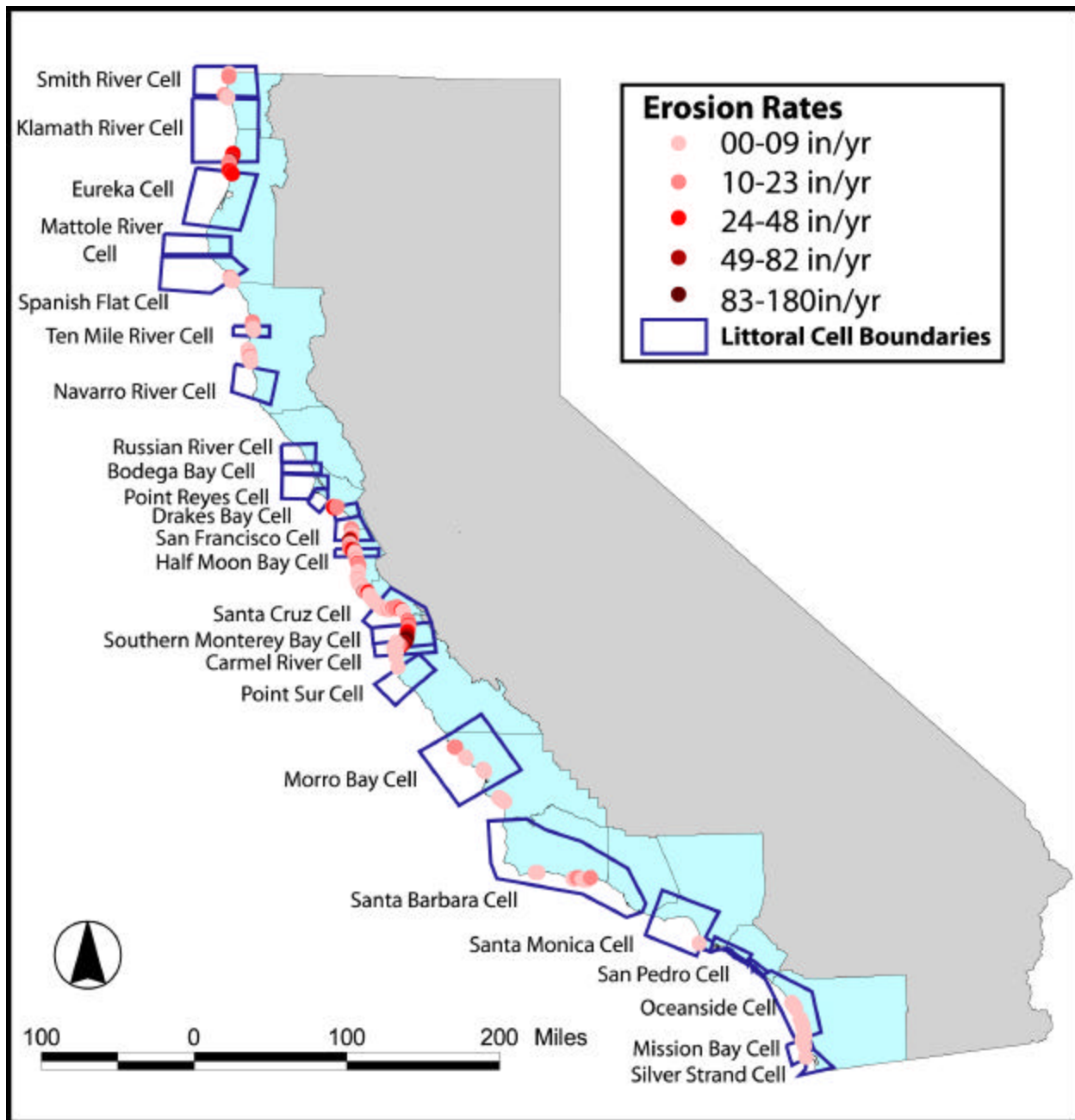


Figure 8.2 Documented erosion rates and littoral cell boundaries for California

(Habel and Armstrong 1977)

8.3 A Statewide Inventory of Sea Cliffs and Their Potential Sediment Contributions to the Littoral System

A statewide assessment of the distribution of sea cliffs, their general lithology or rock type, and their general resistance to erosion was undertaken as part of this study in order to develop a semi-quantitative sense of the potential for sand contribution from the cliffs to California's

littoral system. A complete quantitative assessment of statewide sand contribution from the cliffs, however, is beyond the scope of this investigation. While the determination of cliff height and alongshore length of individual sea cliff segments is relatively straightforward, the measurement of long-term cliff erosion rates and the calculation of the percentage of littoral-sized material and its geographic distribution by rock types along the 1100 miles (1760 km) of California coast will be a major undertaking.

8.3.1 *Distribution of Cliffs*

The coast of California can be broken down into three very general categories: 1) high relief, steep cliffs (Plate 8.4); 2) bluffs eroded into lower relief (less than 300 ft [100 m] in height) marine terraces (Plate 8.5); and 3) coastal lowlands or plains (Plate 8.6). The first two categories may be combined and generally called cliffs. The high relief, steep cliffs of California are composed predominantly of resistant volcanic or granitic rocks and are generally not a major contributor of sand sized material to the littoral budget. The Franciscan Formation (see glossary for definition) is a complex assemblage of different rock types; some that are very resistant to erosion and form promontories or sea stacks, and others that are very weak.



Plate 8.4 Steep, high-relief cliffs south of San Francisco

The lower-relief marine terraces, however, play a more important role in terms of sand contribution. Marine terraces are primarily comprised of Tertiary marine sedimentary rocks, capped by Quaternary terrace deposits which, when eroded, will produce a greater percent of sand sized material than the high relief, steeply cliffed shoreline. After reviewing the *Assessment and Atlas of Shoreline Erosion Along the California Coast* (Habel and Armstrong, 1977), we determined that 72% of the California coastline can generally be designated as sea cliffs. More specifically, 13% of the coastline is high relief, steep cliffs or mountains, and 59% of the coastline is low relief (less than 300 ft [100 m]) wave-cut bluffs or terraces. The high relief, steep

cliffs are found predominantly in Northern California from Del Norte County to Mendocino County and along the Big Sur coast of Monterey and San Luis Obispo Counties. High relief, steeply-cliffed outcrops and headlands can be found along several areas of the Southern California coastline as well; Pt. Loma and the Santa Monica Mountains are two examples.



Plate 8.5 Low-relief, uplifted marine terraces in Santa Cruz County.



Plate 8.6 Coastal lowlands, Orange County.

8.3.2 Distribution of Rock Types

The general geology of the entire California coast was mapped from the California Division of Mines and Geology (CDMG) 1:250,000 scale geologic maps using a Geographic Information System (GIS). While rock types have now been delineated and are accessible in a GIS system for the entire coast, the assessment of the grain size distribution of individual rock units, and therefore their potential sand contributions to the littoral system, is hindered by the nomenclature used on the CDMG maps. For example, CDMG designated rock units as marine, non-marine, volcanic, *et cetera*, which doesn't provide any grain size information. Similar rock units were combined, however, to get an overall sense of their importance along the 72% of the state's shoreline that is backed by sea cliffs.

The most extensive cliff exposures are those aggregated as *Pliocene Marine*, which constitute over a third (39%; 428 miles or 688 km) of the entire 1100 miles (1760 km) of coastline. These are Pliocene-age (2-13 million years old) sedimentary rocks, such as mudstones, siltstones, or sandstones of marine origin. While Pliocene-age sedimentary rocks in general are relatively weak and erodible, there is no way to determine from the CDMG maps whether these sedimentary rocks are sandstones that would contribute sand as they erode, or fine-grained shales, mudstones, and siltstones that do not contribute sand-sized material.

Unconsolidated Quaternary sediments, such as dune sands, marine or non-marine terrace deposits (terrace deposits are sediments that were deposited on a wave-cut platform or terrace when sea level subsided; they may be beach, dune or stream deposits but are usually very sandy), all relatively coarse-grained and potentially-important beach sand sources, constitute the second largest exposures at 28% or just over 300 miles (480 km) of coastline. These materials are usually poorly consolidated and therefore prone to erosion. As a group, based on their erosion patterns and grain size, these sediments are probably the most significant in terms of contribution to the beach sand budget of all coastal cliff materials.

Rock types combined as *Miocene Marine*, *Oligocene Marine*, *Tertiary Marine* and *Cretaceous Marine* make up a combined 19% (335 miles or 540 km) of the state's coastline. Again, there is no way, without detailed additional research on the original references on which the map classifications were based, to discern whether or not these are sand-rich sediments, such as sandstones, or finer-grained rocks, such as shales, mudstones or siltstones.

The assessment of the distribution of rock types is complicated by the fact that the majority of the coast of California consists of uplifted marine terraces, in which underlying sedimentary bedrock is capped by unconsolidated terrace deposits. As the cliffs erode, both the underlying bedrock and the overlying terrace deposits collapse onto the beach, each contributing a different percentage of littoral-sized material to the sediment budget of the particular cell (Plate 8.7).

Detailed topographic and geologic mapping of the bluffs, which requires ground surveys and sampling, is necessary in order to make accurate determinations of the importance of the erosion of specific sections of the cliffs to the littoral budget.

In aggregate, sedimentary rocks and poorly consolidated sediments constitute 939 miles (1502 km) or 85% of the entire 1100-mile coastline of California. Interestingly, the earlier statewide assessment published by the Corps of Engineers in 1971 reported that 86% of the state's coastline was eroding.



Plate 8.7 Eroding coastal bluffs exposing mudstone bedrock at beach level and overlying sandy terrace deposits

The other major units exposed along the shoreline are the *Franciscan Formation* (a complex of older metamorphic and sedimentary rocks that comprises 10% of the coastline), *granitic rocks* (3%), and *Tertiary and Miocene Volcanics* (<1%). In general, these rocks tend to be much harder and more resistant to erosion than sedimentary rocks, and it is often these rock types that form the resistant headlands or points along the state's shoreline. For example, along the Northern California coast, Pt. St. George, Trinidad Head, and Pt. Delgada are all Franciscan Formation outcrops. Bodega Head, Pt. Reyes, Montara Point, Pt. Pinos and Pt. Cypress are all granitic. Proceeding to the south central coast, Pt. Sur, Pt. San Martin, Piedras Blancas and Pt. San Luis are all Franciscan Formation. These are very resistant rock types, most of which are very fine-

grained, erode very slowly and, in the case of the Franciscan Formation and volcanic rocks, are not significant sources of sand for the beach.

8.4 Quantifying Sand Contributions to the Shoreline From Cliff and Bluff Erosion

California's beach sand dominantly comes from rivers and streams and, to a lesser extent, from erosion of the coastal bluffs and cliffs. Although no comprehensive quantitative analysis of sediment sources has been completed for the state's coastline, the regional littoral budgets that have been developed to date, with the exception of the budget for the Oceanside cell, indicate that rivers and streams provide ~ 70-90% of the littoral sand (Bowen and Inman, 1966; California Coastal Commission, 1974; Best and Griggs, 1991a, b; Knur and Kim, 1999; Flick, 1994).

The movement of sand along the California coastline can be understood best in terms of littoral cells or beach compartments (Inman and Frautschy, 1966). A littoral cell can be defined as a segment of coastline that includes sand sources, alongshore transport or littoral drift, and then a sink or sinks for the sand. The most important sand sources for California's littoral cells are the state's rivers, streams and coastal cliffs and bluffs. The major sinks are the many submarine canyons that cross the continental shelf and enter shallow water and the extensive areas of sand dunes. In some areas, southern Monterey Bay for example, sand mining was also a major loss or sink for many years. Many of California's littoral cells have been altered significantly by human activity, which has reduced the availability of sand at the shoreline. The evaluation and quantification of human impacts on sand supply to the various littoral cells along California's shoreline is the core of this study.

8.4.1 Quantifying Cliff Contributions

The annual production of littoral sand from a segment of shoreline through sea cliff erosion (Q_s) is the product of the cross-sectional area of sea cliff (Area = alongshore cliff length times cliff height), the average annual rate of cliff retreat (feet/year), and the percentage of the material that is sand-size (Figure 8.3).

The geology of the sea cliffs varies widely alongshore and, therefore, all of these parameters vary from location to location. As mentioned in Section 8.3.2, where the coastal cliffs consist of uplifted marine terraces, there is typically an underlying and more resistant bedrock unit, which may or may not contain appreciable quantities of sand, and also an overlying sequence of sandy marine terrace deposits. Each of these units must be analyzed for its individual sediment input. In order to make qualitative assessments or quantitative measurements of the contribution of coastal cliff retreat to the littoral system, it is necessary to divide the coast into manageable segments

that are somewhat uniform. These divisions are based on similarities in morphology and rock type along specific segments of coastline. The estimates of sand contributions from the individual segments can then be added to arrive at a total contribution to the beach for a larger area, such as a specific littoral cell (Best and Griggs, 1991a, b).

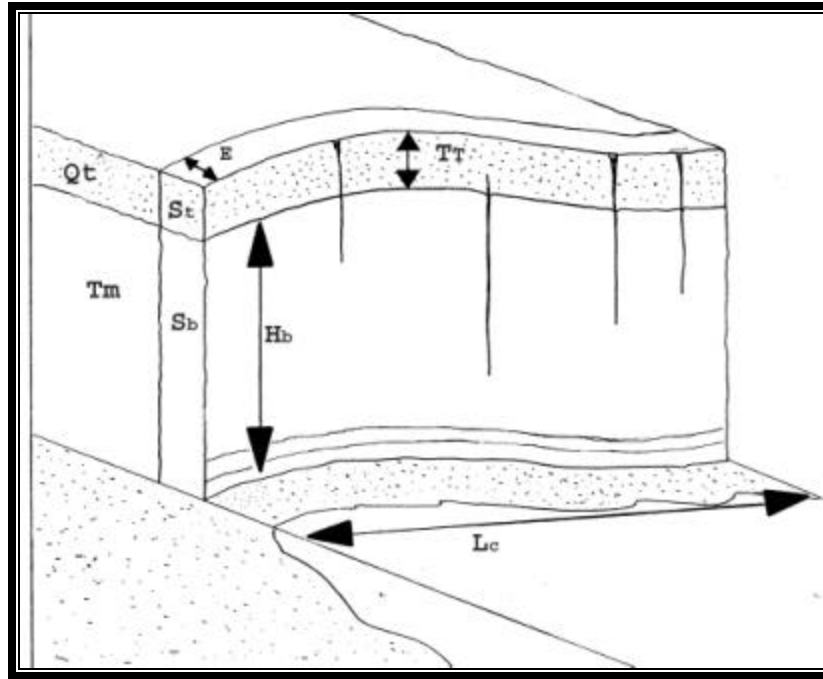


Figure 8.3 Coastal bluff showing components involved in determination of sand contribution
 (St: % sand content of terrace deposit, Sb: % sand content of bedrock, Hb: height of bedrock(ft), Tt: terrace thickness (ft), Lc: length of cliff (ft), E: Erosion rate (ft/yr), Qt: terrace deposit, Tm: Bedrock)

8.4.2 Area of Eroding Sea Cliffs

The area of eroding sea cliff that potentially provides sediment to the littoral budget can be determined from measurements of cliff length and height. Cliff height can either be measured directly in the field or taken from accurate topographic maps. USGS topographic map sheets provide for semi-quantitative estimates of cliff height, although the exact height is not included on these maps except at the locations of specific benchmarks. Where uplifted marine terraces form the coastal cliffs, which is the case for large areas of the California coast, the cliff height is often relatively uniform alongshore for considerable distances and an average height can be used. Where marine terraces form the sea cliff, there are typically two distinct geologic units that are exposed and that contribute to the sand budget: the underlying bedrock, which may vary widely in composition, and the overlying marine terrace deposits, which normally consist of relict beach sand (Plate 8.7) and coarser marine and occasionally non-marine deposits. The thickness of the different units exposed in the sea cliff can be determined from either direct field measurements,

near-horizontal aerial photographs taken at cliff-top altitude from offshore, or through detailed photogrammetric analysis of stereo aerial photographs.

8.4.3 Grain Size of Cliff Materials

A grain size analysis of representative samples of cliff material is necessary in order to quantify the percentage of sand in the cliffs. Samples analyzed in this study include beach sands, unconsolidated marine terrace deposits, and consolidated sedimentary rocks, which were disaggregated or broken down in order to determine their grain sizes. Cliff samples were selected for collection based on how representative they were of individual coastal segments and on access to the representative cliff sites.

Measuring the amount of sand-sized material in a disaggregated sediment sample is straightforward and can be accomplished by shaking the sample through a set of screens or sieves and weighing the amount that remains on a sieve of a given size opening. Where the rock is a highly consolidated or well-cemented shale, mudstone or siltstone, however, disaggregation is very difficult and failure to break the rock down to its constituent particles (as would happen naturally in the surf zone) will yield a sand size percentage that is inaccurate and too high. The importance of bluff erosion to the sand component of the littoral budget would then be overestimated.

In order to accurately determine the amount of sand-size material in the consolidated rock samples from the cliffs, we first physically broke them down to smaller (one or two cm in diameter) fragments. Fifty to 100 grams of the cliff material were then put into a rock tumbler with an equal amount of beach sand from the site (for use as an abrasive) and water. After 12-24 hours of tumbling, the sample was dried and sieved to determine the weight of littoral material remaining after subtracting the weight of the added beach sand. With many samples, this was adequate to completely disaggregate or abrade the bedrock sample so the amount of littoral sized material derived from the rock could be determined. If any larger fragments (coarser than 1 mm) still remained, which was the case for some of the more resistant cliff materials, then they were visually analyzed to determine if they were shale or mudstone fragments that would not contribute to the littoral budget; this material was discounted. This approach provided an accurate measurement of the actual percentage of resistant littoral-size material present in each bluff sample (Appendix B). These percentages were then used in the calculations of the littoral sand contributed from each particular segment of bluff sampled and analyzed.

While it is common practice to refer to most beach sediment as “sand,” grain sizes found on beaches in California range from very fine sand to cobbles. Sand is defined as all particles between 0.062 mm and 2 mm in diameter; this grain size is characteristic of most California beaches. Very fine-grained sand, ranging from 0.062 to 0.125 mm in diameter, doesn’t usually

remain on most California beaches due to the high-energy wave environment. Hicks (1985), in an investigation of littoral transport processes and beach sand in northern Monterey Bay, discovered that there was a “littoral cut-off diameter”, or a grain size diameter, characteristic of particular segments of coast, that serves as a functional grain size boundary in that very little material finer-grained than this diameter is found in the beach. The littoral cut-off diameter is primarily a function of wave energy along any particular beach or stretch of coast. Studies along the coast of northern Santa Cruz County (Hicks, 1985; Best and Griggs, 1991a, b), which is a relatively high-energy exposed coast, indicate a littoral cut-off diameter of ~0.18 mm. Analysis of beach sand samples collected throughout the Santa Barbara cell in this study indicate an approximate littoral cut-off diameter of 0.125 mm, whereas in the Oceanside cell, the cut-off diameter is finer-grained (0.0875 mm). In most beach samples analyzed, ~95-98% of the sand in the beaches of these cells was coarser-grained than this cut-off diameter. It is important to realize that 0.062mm, the smaller value used to define “sand” on the Wentworth scale, is simply one grain-size designation that was somewhat arbitrarily defined as the dividing line between silt and sand; it carries no specific hydraulic distinction. Previous studies (e.g. Bowen and Inman, 1963; Diener, 2000) that assumed all sediment coarser than 0.062 mm is suitable beach sand for a particular site have probably overestimated the local cliff contribution.

8.4.4 Cliff Erosion Rates

Another factor in determining the amount of sand contributed by cliff erosion to a littoral cell is the average rate of sea cliff retreat. Episodic and locally-variable rates of cliff retreat result from a combination of 1) alongshore differences in the strength of cliff materials (Griggs and Johnson, 1979; Benumof and Griggs, 1999), 2) the infrequent coincidence of high tides and extreme storm waves capable of causing significant erosion and removing debris from the base of the cliff, 3) concentration of wave energy due to local bathymetry (Benumof et al., 2000), and 4) the presence or absence of a protective beach. Rates of bluff retreat also may be influenced by large earthquakes, such as the 7.1 magnitude October 17, 1989 Loma Prieta Earthquake. This was the largest earthquake to affect the Central coast since the 1906 San Francisco earthquake, and it produced isolated cliff failures from Marin to Monterey counties (Plate 8.2; Plant and Griggs, 1990).

Where either qualitative or quantitative analyses have been completed (Griggs and Johnson, 1979; Benumof and Griggs, 1999), it is evident that the lithology and structural weaknesses of the cliff-forming materials exert the dominant control on rates of seacliff retreat.

Rates of sea cliff erosion can be computed from a comparison of time-sequential aerial photographs, ground photographs or historic coastal surveys and maps. Typically, the position of the sea cliff edge at specific locations or transects is identified on individual maps or aerial photographs over the longest time span for which data are available and is used to determine

long-term average annual cliff erosion rates. There are a number of techniques with varying degrees of accuracy for making these measurements; the more precise measurements are the most time consuming and hardware/software intensive (Moore, 2000).

Because of the time involved and the equipment and aerial photographic or map database needed to accurately measure long-term sea cliff erosion rates, there have been few attempts to calculate bluff retreat rates in California. *Living with the California Coast* (Griggs and Savoy, 1985) included input on a regional basis from a group of coastal geologists in California, and maps included in that volume incorporate the site-specific cliff erosion rates known at that time. More recently, the city of Pismo Beach, California completed a bluff erosion study in which bluff retreat rates were estimated by analyzing aerial photographs dating back to 1954, topographic maps, and recent field measurements (Earth Systems Consultants Northern California, 1992). Moore, Benumof and Griggs (1998) completed coastal erosion studies for San Diego and most of Santa Cruz County in which bluff retreat rates were calculated using photogrammetric analysis. Diener (2000) calculated cliff retreat rates from Point Conception to Santa Barbara by comparing United States Geological Survey (USGS) 7.5' topographic maps produced in 1947 and a set of 1:25,000 scale aerial photographs taken in 1997.

In a statewide coastal hazards study (Griggs, Pepper and Jordan, 1992), it was determined from interviews with local government planning staff that the most frequently cited data need was that of shoreline and bluff erosion rates. Nearly half of the respondents indicated a need for such information. Yet, we have found through the present study that there are still very few additional published or easily accessible cliff erosion rates beyond those previously published by Moore et al. in 1998 for Santa Cruz and San Diego counties. There have been a number of site-specific studies for individual parcels where cliff erosion rates were required as a condition for development permits, but there has been no attempt to consolidate these for broader application.

8.5 Statewide Armoring and the Reduction of Beach Sand Supply From Coastal Bluffs

We have shown that eroding bluffs and cliffs make up about 950 miles (1520 km; 72%) of the coast of California. Specifically, 13% of the coast consists of more resistant, high relief, steep cliffs or mountains, and 59% of the shoreline is low relief (less than 300 ft [100 m] high) wave-cut bluffs or terraces. The low bluffs typically consist of a sedimentary rock basal section overlain by sandy, unconsolidated terrace deposits. These bluffs often are cut into nearly flat, uplifted marine terraces and are intensely developed (Plate 8.8). Because the sedimentary rocks and the overlying terrace deposits are relatively weak and highly susceptible to both marine and subaerial erosion, and because they have been intensely developed, many of these areas now have been armored to protect existing development. Halting coastal bluff erosion has reduced the amount of sand contributed by the eroding bluffs to the littoral budget.

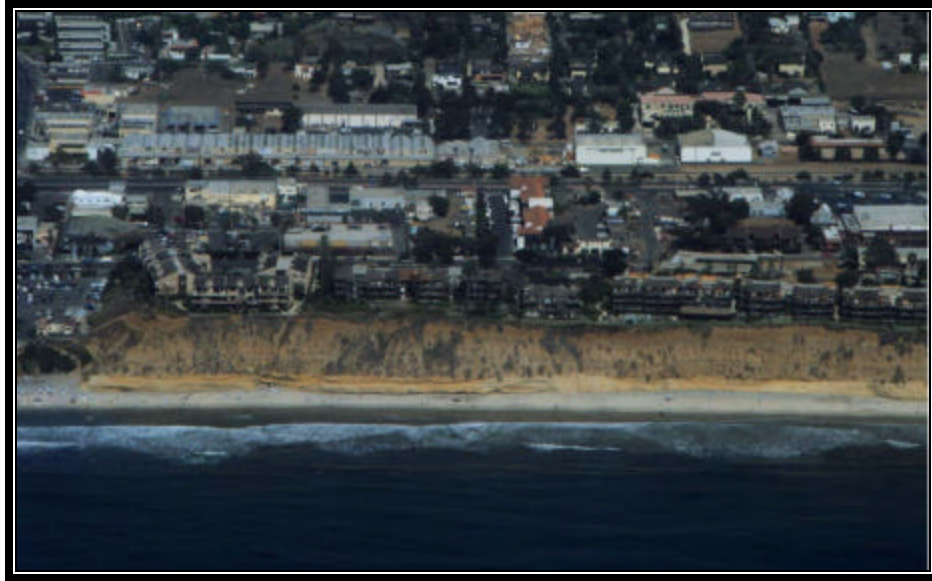
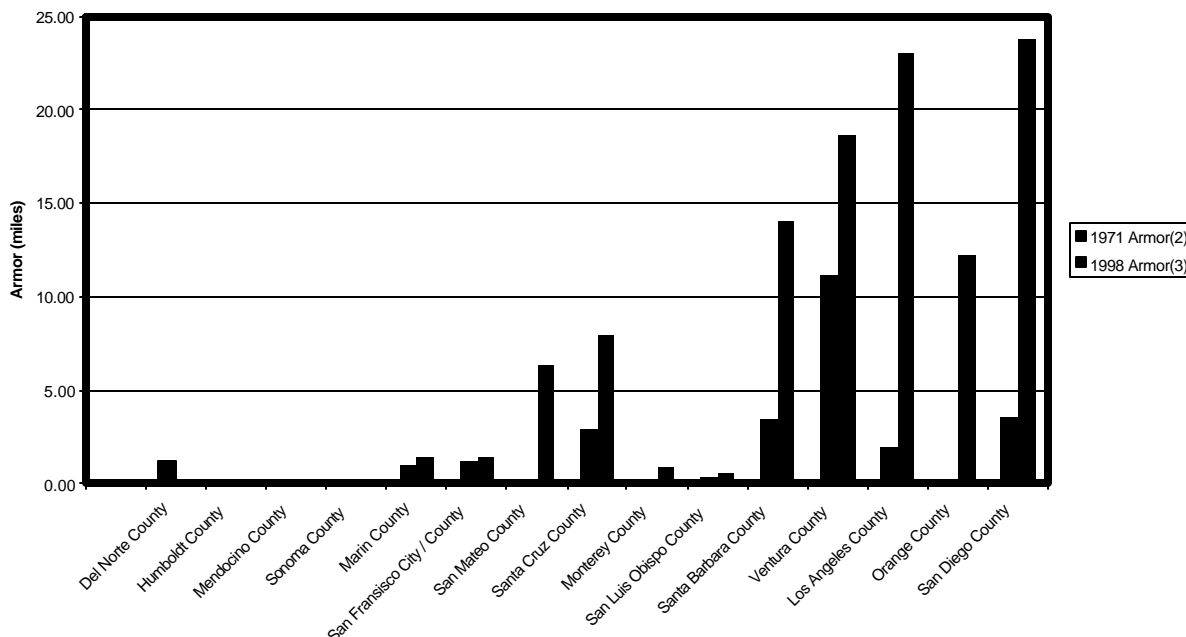


Plate 8.8 Developed terrace and bluffs at Solana Beach, San Diego County

All research and studies to date, with the possible exception of those focused on the Oceanside littoral cell, indicate that the volume of beach sand contributed by bluff erosion along the shoreline of California is substantially less than the volume contributed to littoral cells from rivers and streams. However, as fluvial contributions have decreased, bluff contributions have become more important in local sediment budgets. Thus, coastal armor, which prevents bluff sediment contributions from reaching the beach, could have a significant impact on the sediment budget in individual littoral cells. As the development of the Southern and Central California coast has expanded, and as coastal storm damage has intensified since 1978, the extent of coastline protected by armor has continued to increase.

8.5.1 Previous Inventories of Coastal Armor

In the 1971 U. S. Army Corps of Engineers statewide shoreline inventory, 26.5 miles (42.7 km) of California coastline (2.5%) were listed as protected by some sort of armor (exclusive of breakwaters and groins; Table 8.1). Six years later, in 1977, the California Department of Navigation and Ocean Development, now the Department of Boating and Waterways, determined that 62 miles (~ 100 km) or 5.7% of the state's coastline had been protected by shore-parallel engineering structures, and an additional 18.8 miles (30.2 km; 1.7%) were protected by breakwaters, for a total of 81 miles (130.2 km) or 7.4% of the coast. The most recent inventory of armoring in the San Diego region, *Shoreline Erosion Assessment and Atlas of the San Diego Region*, was done by the Department of Boating and Waterways in conjunction with the San Diego Association of Governments (Flick, 1994). This atlas provided armor location maps for the San Diego region, but did not include a summary of the total linear miles of armor.

Table 8.1 Comparison of Length of Armor by County in 1971 versus 1998

(2) From 1971 National Shoreline Study California Regional Inventory, US Army Corp of Engineers

(3) From 1998 Aerial Oblique Digital Photography Transferred to GIS

There are significant challenges to accurately quantifying the amount of coastline that has been armored. This section points out and explains some of the data discrepancies discovered in this investigation. It is not clear how the armor data that were included in either the 1971 USACOE or the 1977 state study were obtained.

In *Living with the California Coast* (Griggs and Savoy, 1985), a group of coastal geologists analyzed coastal hazards mile by mile along the state's coastline. Their maps indicate that approximately 85 miles (136 km), 7.7% of the coast, were armored by seawalls or revetments, and another 20 miles (32 km) were protected by breakwaters, for a total of 105 miles (168 km) of armor by 1985 (9.5% of the entire 1100 miles (1760 km) of coastline). For that study, the individual geologists who knew the specific sections of shoreline mapped the distribution of armor, so this was probably an accurate assessment of the extent of armored areas at that time.

In a subsequent study analyzing the state's coastal hazard policies and practices, using first-hand interviews with local government planners, Griggs, Pepper and Jordan (1992) reported that a total of 130 miles (208 km) or 11.8% of the coast were now protected by some form of hard structure. The study looked at the extent of armor by city and county. As might be expected, the heavily populated and developed central and southern portions of the state's coast had been protected to a far greater degree than the less-populated northern coast. For example, seventy-seven percent of the 17-mile (27 km) coastline between Carpinteria and Ventura and 86% of the

8-mile coastline from Oceanside to Carlsbad had been protected. In comparison, only 8% of the 45 miles (73 km) of Del Norte County had been protected at the time of the study.

The California Coastal Commission, as part of their Regional Cumulative Assessment Project (ReCAP), reviewed coastal armoring practices in the Monterey Bay Region (Plate 8.9) as well as the Santa Monica Mountains/Malibu area. For the Monterey Bay Region, from the San Mateo/Santa Cruz county line south through Point Lobos in Monterey County, aerial photographs from 1978, 1986, and 1991 were compared to determine changes in armoring. In 1978, there were approximately 9.6 miles (6 miles in Santa Cruz County and 3.6 miles in the ReCAP portion of Monterey County) of armoring in this area. This number increased to 11.9 miles (8.2 miles of armoring in Santa Cruz County and 3.7 miles in the ReCAP portion of Monterey County) of armoring in 1986. By 1993, there was only a slight increase in the armoring of Santa Cruz County, bringing the total to 12 miles (8.2 miles of armoring in Santa Cruz County and 3.7 miles in the ReCAP portion of Monterey County) of armoring for this study area. These numbers do not include protection by means of breakwaters, jetties or groins; they also do not include the addition of rock to existing walls for maintenance purposes (California Coastal Commission, 1995).



Plate 8.9 Rip-rap armoring the bluffs at the mouth of Corcoran Lagoon, Santa Cruz County

The study site for the Santa Monica Mountains/Malibu ReCAP study extends from Point Mugu in Ventura County to Topanga Canyon in Los Angeles County. Using aerial photographs from 1978 along with an analysis of Commission permit actions, ReCAP found that approximately 11.4 miles or 35% of the study area were protected by seawalls, rip-rap, or retaining walls. From 1978 to 1996, the California Coastal Commission authorized shoreline protective structures along approximately 2.8 miles of shoreline in this study area. Thus, the total amount of shoreline protective armoring (including approximately 0.6 miles of armoring that is not permitted) at the

time of the ReCAP study for the Santa Monica Mountains/Malibu area was 14.8 miles (California Coastal Commission, 1998).

8.5.2 *Current Inventory of Coastal Armor*

To update the extent of coastal armor along the coast of California, a database of coastal structures was created in a GIS. This was accomplished using a combination of oblique video, and photographic coverage of the coast obtained during the past several years. The more developed portions of the state's coast are the areas where both urbanization and seawall construction are the most extensive and also where the photographic coverage is the most complete and up-to-date.

We also contacted planners in individual cities and counties to determine what their permit records showed for the amount of armor that had been permitted in their individual municipality. Several important findings came out of these inquiries. For the most part, few local governments either compile or track the amount of armor that has been built. In most cases, there was either no response or the staff planner was not able to provide the information and didn't know who could. In one case, we were able to contact the same staff person we contacted in the 1992 study and were given a value for the amount of armor that turned out to be less than the value provided nine years earlier. We then discovered that in the 1992 interviews some local government staff provided data on not only shore-parallel coastal seawalls or rip-rap, but also armoring along channelized river mouths and within harbors to protect shorelines. This provided a strong rationale for developing accurate recent values for the extent of coastal armor.

Video coverage of the area from San Diego to Santa Barbara flown in 1998 was utilized, as was 2001 digital and video photography of the area from San Francisco to Santa Cruz. Hard armor structures were visually interpreted from the video coverage and mapped in a GIS format. The armoring of the remaining north and central coast areas not covered by the digital video were delineated using a combination of *Living with the California Coast* (Griggs and Savoy, 1985) and, where we could obtain data, from the local government planning or public works departments. Recent photo coverage was not available for most of the coast north of San Francisco. This is an area, however, where overall coastal development and consequently coastal protection is of relatively limited extent.

Even with low-flying aircraft and high-resolution oblique digital photography or digital video, in some cases it was difficult to identify low seawalls and rip-rap where they were low relief, partially covered with sand or vegetation, or otherwise obscured. Thus, the values we have determined for the length of armoring along the coast are minima, as there may be structures that simply are not visible from the air. There is no efficient way to accurately document the extent of armor without physically walking the protected areas.



Plate 8.10 Rip-rap armoring coastal bluffs in Santa Cruz



Plate 8.11 A curved-face concrete seawall under construction in Monterey Bay

The armor was divided into 2 categories: rip-rap/revetment (Plate 8.10) and concrete, timber and sheet-pile seawall (Plate 8.11). Approximately 102 miles (165 km; 9%) of the state's coastline are presently armored; 58 miles (93 km; 57%) of this armor protect coastal lowlands or dunes while the remaining 44 miles (72 km; 43%) of the armor protect sea cliffs. Of the total armor, 41% is concrete, timber and sheet-pile seawalls, and 59% is rip-rap/revetment or a combination thereof.

The total percentage of the coast verified as armored in this investigation (9% or 102 miles (165 km)) is less than that reported in the last inventory (11.8% or 129 miles (208 km); Griggs, Pepper and Jordan, 1992). As discussed above, we believe that this is due to some local government planners having reported the length of rip-rap or other structures that were protecting interior margins of marinas and flood or bank control projects along river mouths in their estimates of total armoring in their region. Another source of error may be the inability in some cases to recognize low relief structures or those that have been designed to match the existing bedrock (Plate 8.12) from oblique low altitude aerial photography.



Plate 8.12 A seawall in Encinitas designed to protect the base of the bluff and visually blend with existing bedrock

8.6 The Oceanside and Santa Barbara Littoral Cells: Contribution of Sand From Sea Cliff Erosion and Impacts of Coastal Armoring

To assess the direct impact of coastal armor on the contribution of littoral sediment from bluff erosion, two littoral cells were chosen for detailed investigation. The Oceanside and Santa Barbara cells (Figures 8.4 and 8.5) were selected to provide a littoral cell-specific sand budget analysis, including the pre-development budget and the extent of human impact on the budgets.

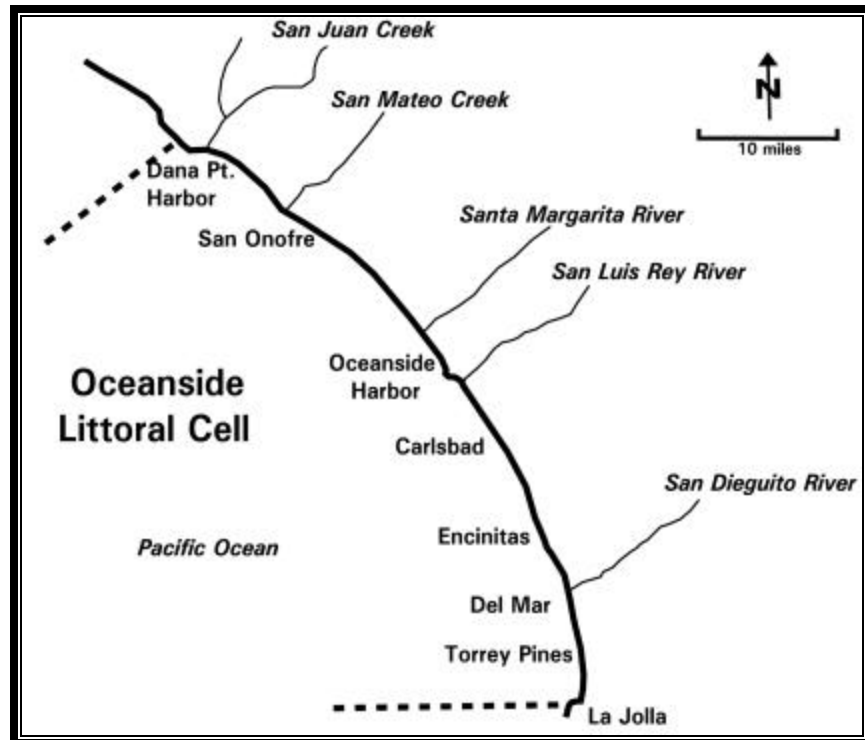


Figure 8.4 Location map for the Oceanside Littoral Cell

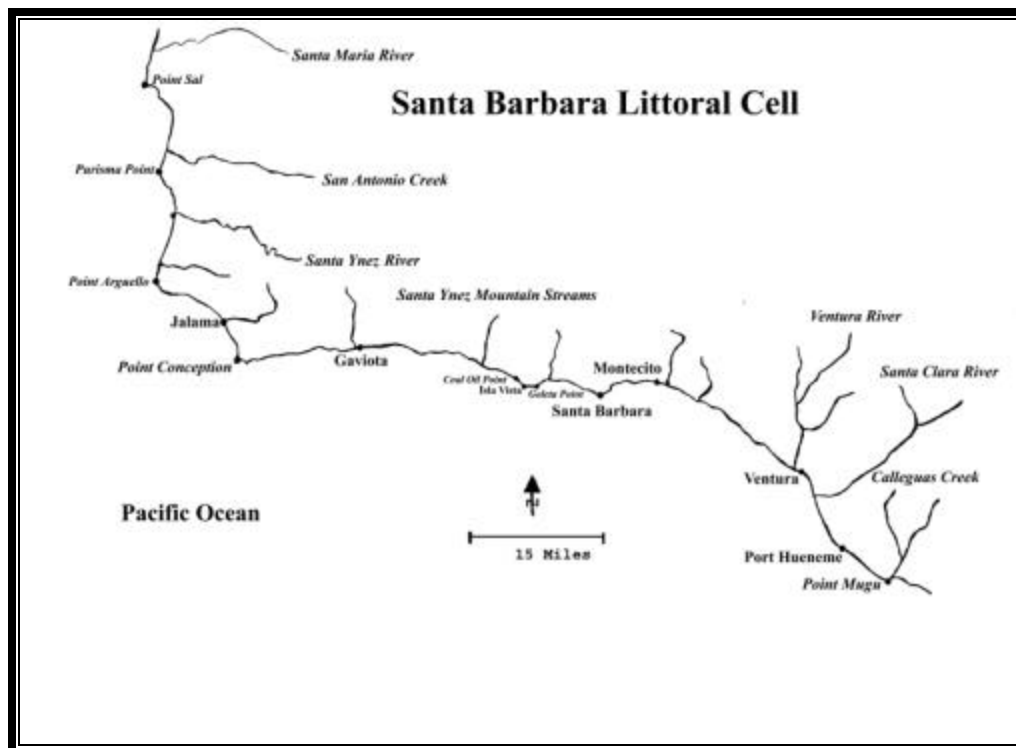


Figure 8.5 Location map for the Santa Barbara Littoral Cell

8.6.1 Oceanside Littoral Cell

General description of Oceanside littoral cell

The Oceanside littoral cell extends approximately 48 miles (76.5 km) from Dana Point Harbor south to La Jolla Submarine Canyon (Figure 8.4; Inman. and. Frautschy, 1966; Robinson, 1988). The upcoast San Pedro cell terminates at Newport Submarine Canyon, just upcoast of Dana Point. San Juan Creek, San Mateo Creek, the Santa Margarita River, and the San Luis Rey River are the major sources of fluvial sediment input to the Oceanside cell. Sand moves southward in the cell and eventually enters the head of La Jolla submarine canyon, which is within a few hundred yards of the shoreline, just offshore from Scripps Institution of Oceanography. The canyon extends offshore in a southwesterly direction for about 33 miles (53 km), eventually discharging sediment into San Diego Trough.



Plate 8.13 Cliffs at Torrey Pines, San Diego County

Sand contribution from the bluffs of the cell

Seventy-three percent of the Oceanside littoral cell consists of eroding sea cliffs that range in height from 25 to 100 feet (7.5 to 31 m), with the notable exception of the Torrey Pines area where cliffs reach heights of over 300 feet (90 m; Plate 8.13). At most locations in the Oceanside cell, the sea cliffs consist of two units: relatively resistant Eocene bedrock, composed of a variety of sedimentary rocks ranging from mudstone to sandstone and conglomerate, and a capping unit of unconsolidated Pleistocene marine terrace material. More resistant Cretaceous bedrock, which is over 80 million years old, comprises the headlands found from La Jolla to Point Loma. Once eroded, the bedrock and terrace deposits provide a wide range of grain sizes to the littoral budget. By analyzing the grain size distribution of sand on nine beaches in the Oceanside Cell, the littoral cut-off diameter was determined to be approximately .088 mm (3.5 Phi). Annual cliff

erosion rates in this littoral cell (Figure 8.2; Figure 8.6), determined by Benumof and Griggs (1999) and Moore, Benumof and Griggs (1998) using soft copy photogrammetry (Moore, 2000) and expressed as weighted averages for distinct segments of the cell, vary from ~ 4 inches (10 cm) to about 8 inches (20 cm) per year depending on the bedrock type, rock strength and structural weaknesses, wave climate, and terrestrial processes.

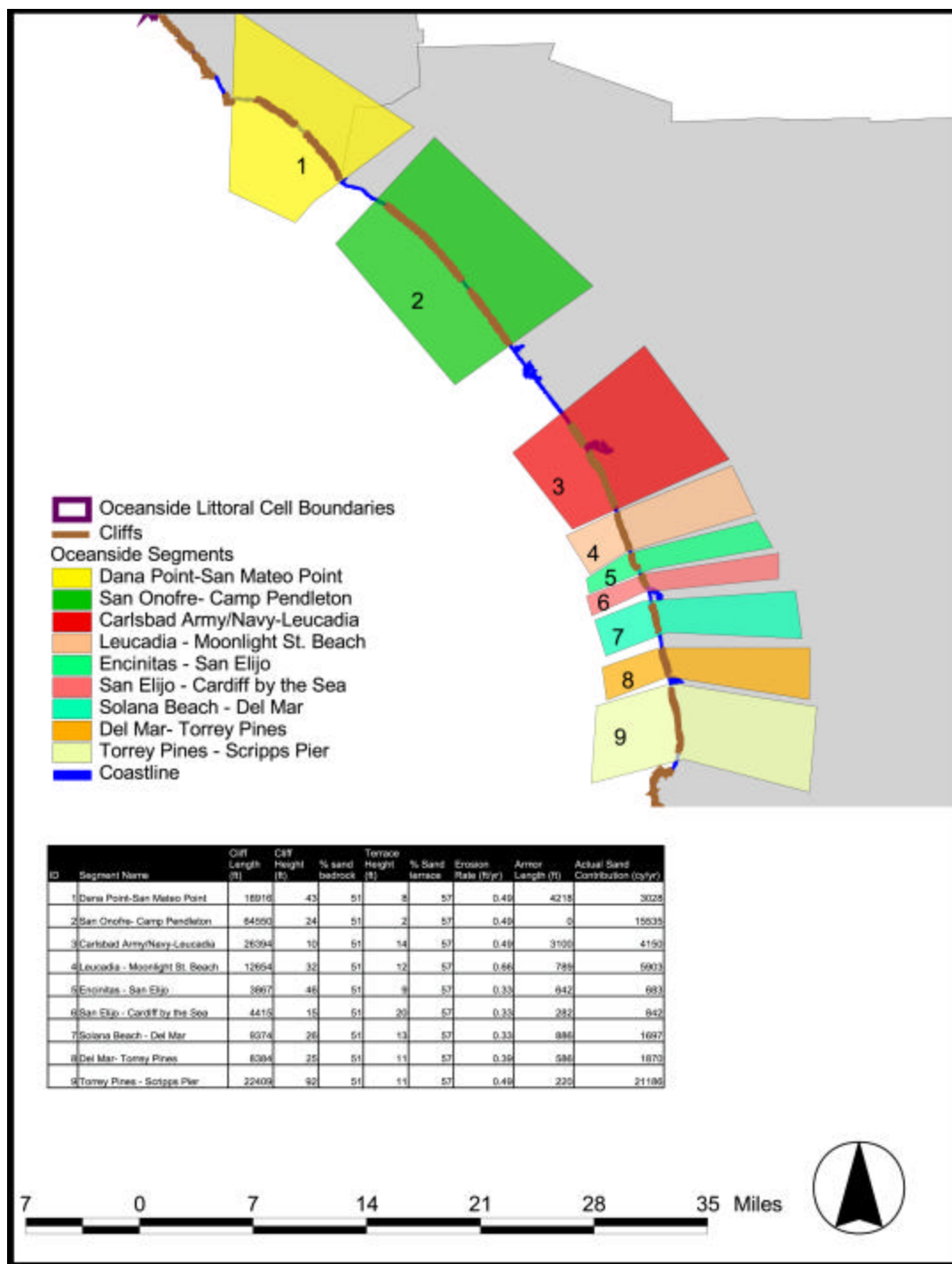


Figure 8.6 The Oceanside littoral cell showing segments used in sand contribution calculations

Using the littoral cut-off diameter of .088 mm, it was determined, from the breakdown and grain size analysis of samples collected from the bedrock (7 samples, one of which had an anomalously-low sand content and was eliminated) and terrace deposits (6 samples, one of which had an anomalously-low sand content and was eliminated) from the cliffs of the cell (Appendix B), that these units are comprised of, on average, 51% and 57% respectively of beach-size material.

Using the area of eroding cliff (linear extent and height or thickness of both the bedrock and terrace deposits taken from field measurements), multiplying this by the average percentage of littoral-size material in each geologic unit, and the average annual erosion rates calculated by Benumof and Griggs (1999) and Moore, Benumof, and Griggs (1998), it was determined that the “natural” cliff contribution of sand to the beaches of the Oceanside cell (without taking into account the reduction of sand by armor structures) is approximately 67,300 yds³ (51,400 m³) per year.



Plate 8.14 Armored bluffs at Del Mar, San Diego County

Extent of coastal protection structures and impact on sand production from cliff erosion

The historical human response to sea cliff erosion in the Oceanside Cell, as well as for most of Southern California, has been to armor the cliff with hard structures (e.g. concrete seawalls, revetments, etc.). In the Oceanside Cell alone, 20% of the sea cliffs have some sort of protective armor (Plate 8.14; Figures 8.7 and 8.8). This armor, while protecting bluff-top development from potential erosion, blocks sand that naturally would be contributing to the littoral budget. By dividing the cell into distinct segments with similar cliff morphology (height/thickness of bedrock and terrace deposits) and erosion rates, we quantified the littoral sand contribution from each coastal segment (Figure 8.6; Table 8.2). By then documenting the extent of bluff armoring for each of these segments (Table 8.2; Figures 8.7 and 8.8), we were able to calculate the amount of littoral material that is prevented by armor from reaching the beach. The armor protecting the bluffs of the Oceanside Cell presently prevents approximately 12,400 yds³/yr (~9,500 m³/yr), or 18%, of the “natural” cliff contribution of sand-sized material from entering the littoral cell. As the coastline continues to be armored, the sand provided to the beaches from the cliffs will be reduced further.

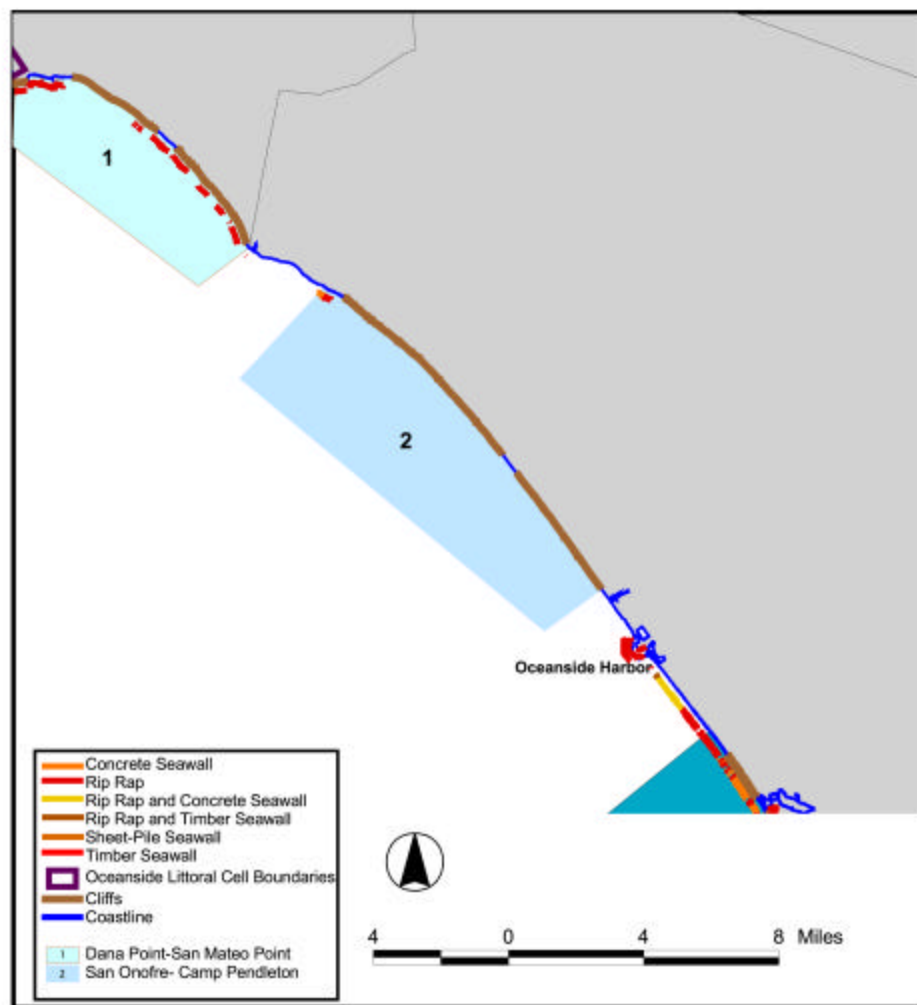


Figure 8.7 Armor in the Oceanside Cell- Dana Point to Oceanside

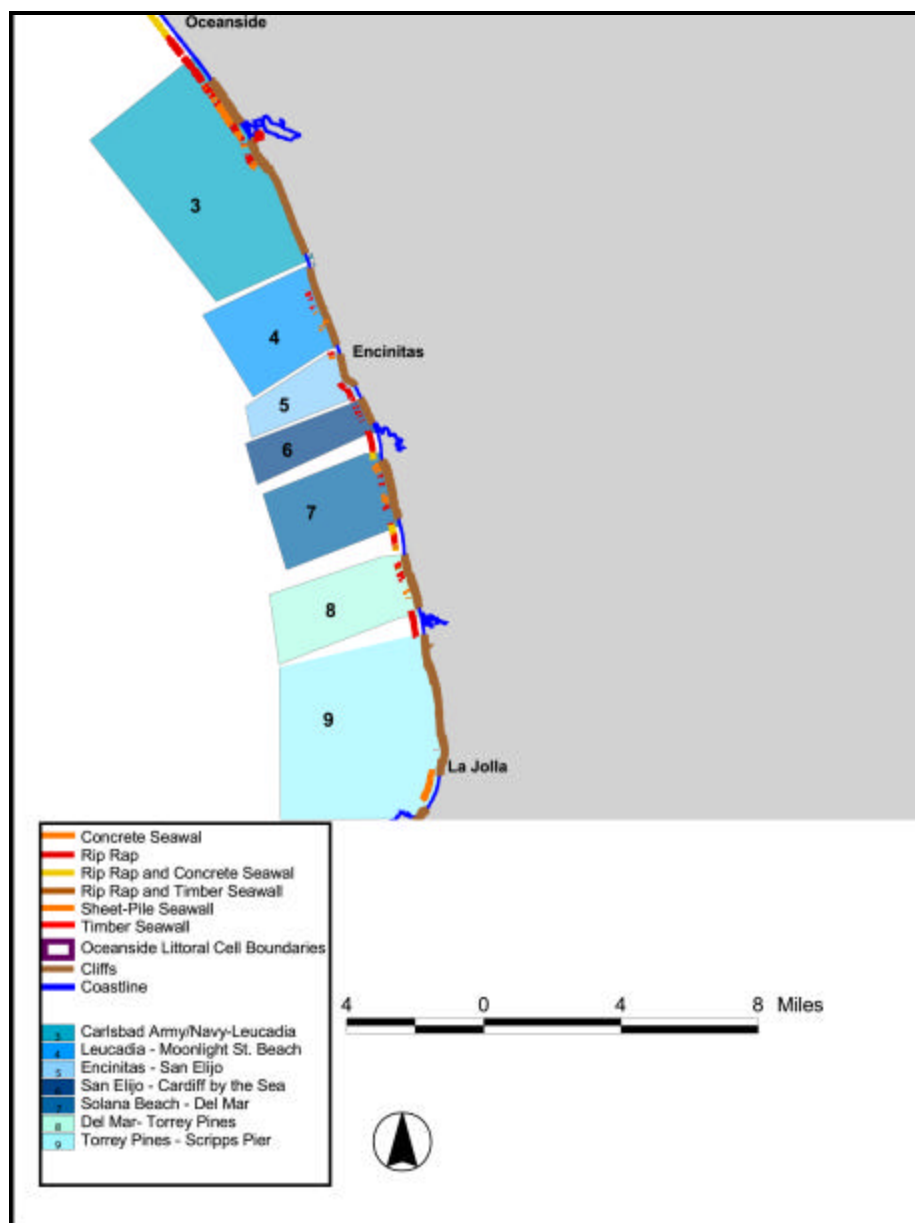


Figure 8.8 Armor in the Oceanside Cell-Oceanside to La Jolla

Impact of bluff armoring on the overall sand budget for the Oceanside littoral cell

In addition to determining the present-day input of littoral sediment to the Oceanside cell from bluff retreat ($\sim 54,900 \text{ yds}^3/\text{yr}$), we also estimated the sand supplied from stream discharge ($\sim 132,000 \text{ yds}^3/\text{yr}$; Figure 8.9; Section 7.1, this report); these two sources total $\sim 186,900 \text{ yds}^3/\text{year}$.

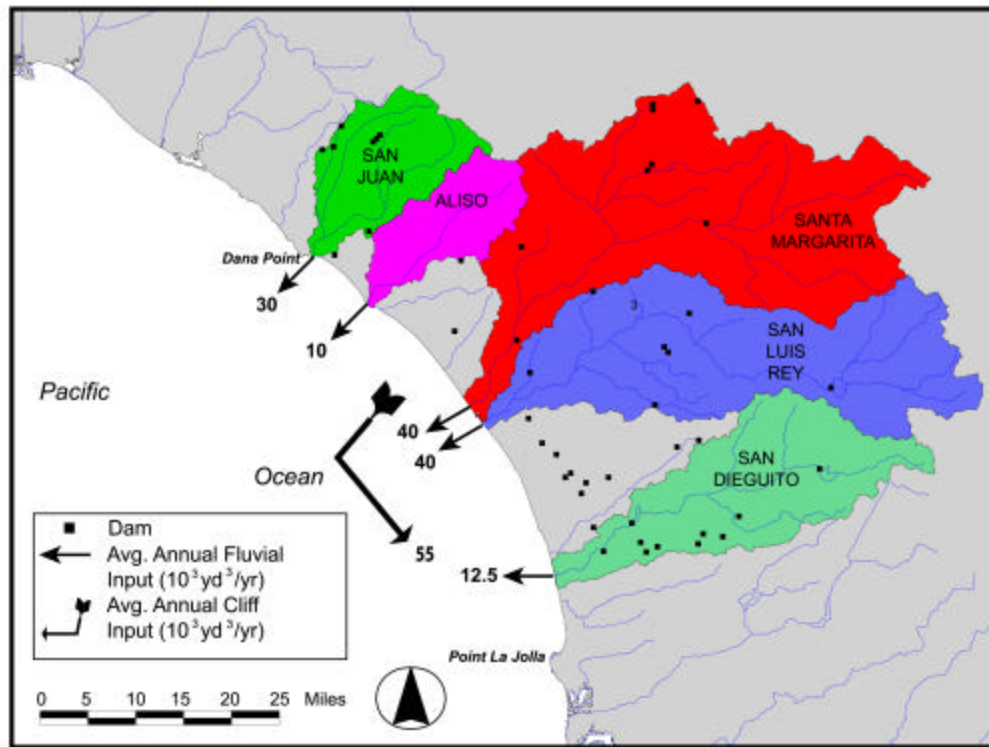


Figure 8.9 Sediment inputs to the Oceanside Littoral Cell

Flick (1994) includes a sand budget for the Oceanside cell that also contains values for both natural and present-day stream delivery, as well as a combined value for cliff retreat, terrace and gully erosion determined by Robinson (1988). In order to arrive at a total sand budget, we need to add the quantity of sand provided by gully and upland terrace erosion that has been deemed by others (Kuhn and Shepard, 1984) to be significant to the cell. To obtain this value, we determined the difference between Robinson's combined cliff retreat, terrace and gully erosion volume (355,000 yds³/year) and our natural cliff sand contribution volume (67,300 yds³/year) to arrive at a value for gully and terrace erosion. This component adds an additional 287,700 yds³/yr.

"Natural" bluff erosion historically has contributed ~10% of the beach sand to the Oceanside cell, with stream input providing 45% and terrace and gully erosion providing the remaining 45% of the sediment reaching the coastline (Table 8.2). The impact of bluff armor on the total sediment contribution for the Oceanside cell is a reduction of 12,400 yds³/yr, or 3%, of the total littoral budget; at present, the cliffs contribute 11% of the beach sand to the littoral cell, with streams and upland terrace and gully erosion providing the remaining 89% of the total sediment input of 474,533 yds³/yr.

Table 8.2 Sand Contributions And Reductions Due To Coastal Armoring For The Oceanside And Santa Barbara Cells

CLIFF LOCATIONS	site length		bedrock thickness		% sand	terrace thickness		% sand	erosion rate		natural sand contribution		armor length		actual sand contribution		sand blocked by armor	
	meters	feet	meters	feet		meters	feet		m/yr	ft/yr	m ³ /yr	cy/yr	meters	yards	m ³ /yr	cy/yr	m ³ /yr	cy/yr
OCEANSIDE																		
Scripps Pier to Torrey Pines	6832	22409	28	92	51.10%	3.4	11	57.4%	0.15	0.49	16662.84	21,828	201	220	16,173	21,186	491	642
Torrey Pines to Del Mar	2556	8384	7.7	25	51.10%	3.4	11	57.4%	0.12	0.39	1805.45	2,365	536	586	1,427	1,870	379	496
Del Mar to Solana Beach	2858	9374	8	26	51.10%	3.9	13	57.4%	0.10	0.33	1808.14	2,369	810	886	1,296	1,697	513	671
Cardiff by the Sea to San Elijo State Beach	1346	4415	4.6	15	51.10%	6.2	20	57.4%	0.10	0.33	795.41	1,042	258	282	643	842	153	199
San Elijo to Encinitas	1179	3867	14.1	46	51.10%	2.8	9	57.4%	0.10	0.33	1038.97	1,361	587	642	521	683	518	678
Moonlight state beach to Leucadia	3858	12654	9.9	32	51.10%	3.7	12	57.4%	0.20	0.66	5542.17	7,260	721	789	4,506	5,903	1,038	1,357
Leucadia to Carlsbad Army and Navy	8047	26394	3.1	10	51.10%	4.3	14	57.4%	0.15	0.49	4891.33	6,408	2834.8	3100.2	3,168	4,150	1,726	2,257
Camp Pendleton to San Onofre	19680	64550	7.3	24	51.10%	0.5	2	57.4%	0.15	0.49	11859.07	15,535	0	0.0	11,859	15,535	0	0
San Mateo Point to Dana Point	5767	18916	13.2	43	51.10%	2.3	8	57.4%	0.15	0.49	6976.97	9,140	3856.5	4217.5	2,311	3,028	4,673	6,112
sum											51,380	67,308	9,804	10,722	41,905	54,895	9,490	12,413
SANTA BARBARA																		
Rincon Point- Loon Point	5540	18,171	30	98.4	0.1%	0.5	1.6	60%	0.305	1.0	557	730	1,804	1,973	376	492	181	238
Loon Point to Fernald Point	2934	9,624	21	68.9	0.1%	1.7	5.6	60%	0.305	1.0	931	1,220	2,087	2,282	269	352	662	867
Fernald Point to SB Cemetery	1350	4,428	29	95.1	0.1%	0.1	0.3	60%	0.305	1.0	37	48	468	512	24	31	13	17
SB Point to Lighthouse	2080	6,822	14	45.9	0.1%	3	9.8	60%	0.152	0.5	575	753	567	620	418	548	157	205
Lighthouse to Arroyo Burro	1995	6,544	14.3	46.9	0.1%	4	13.1	60%	0.152	0.5	734	962	481	526	557	730	177	232
Arroyo Burro to Hope Ranch	4200	13,776	13.7	44.9	0.1%	0.5	1.6	60%	0.152	0.5	201	263	372	407	183	240	18	23
Goleta Beach to Goleta Point	1600	5,248	6.5	21.3	0.1%	3.5	11.5	60%	0.305	1.0	1,027	1,346	345	377	806	1,056	222	290
Goleta Point to Coal Oil Point	1960	6,429	10.2	33.5	0.1%	4	13.1	60%	0.152	0.5	720	943	712	779	458	601	262	343
Coal Oil Point to Naples	7280	23,878	10.2	33.5	0.1%	1	3.3	60%	0.152	0.5	677	887	1,359	1,486	551	721	126	166
Naples to Port Orford	23640	77,539	10.2	33.5	0.1%	1	3.3	60%	0.152	0.5	2,198	2,880	2,566	2,806	1,960	2,567	239	313
Port Orford to Jalama	28331	92,926	6.5	21.3	0.1%	0.1	0.3	60%	0.076	0.2	144	188	3,408	3,727	126	165	17	23
Jalama to Spring Canyon	31596	103,635	7.6	24.9	0.1%	2	6.6	60%	0.076	0.2	2,907	3,809	0	0	2,907	3,809	0	0
sum											10,708	14,028	14,169	15,495	8,635	11,312	2,073	2,716

8.6.2 Santa Barbara Littoral Cell

General description of cell--extent, inputs and outputs

The Santa Barbara littoral cell is one of the longest littoral cells in Southern California, extending, for the purposes of our study, 143 miles (230 km) from the mouth of the Santa Maria River, around Point Conception, and terminating at Point Mugu into the Mugu Submarine Canyon (Figure 8.5). At Point Conception, the California coastline makes an abrupt 90-degree shift from a north/south orientation to an east/west orientation. The Santa Maria, Santa Ynez, Ventura and Santa Clara rivers all provide significant volumes of sand to the cell. For this study, the coastline in the cell has been divided into segments (Figure 8.10) in order to better identify the inputs to the littoral budget.

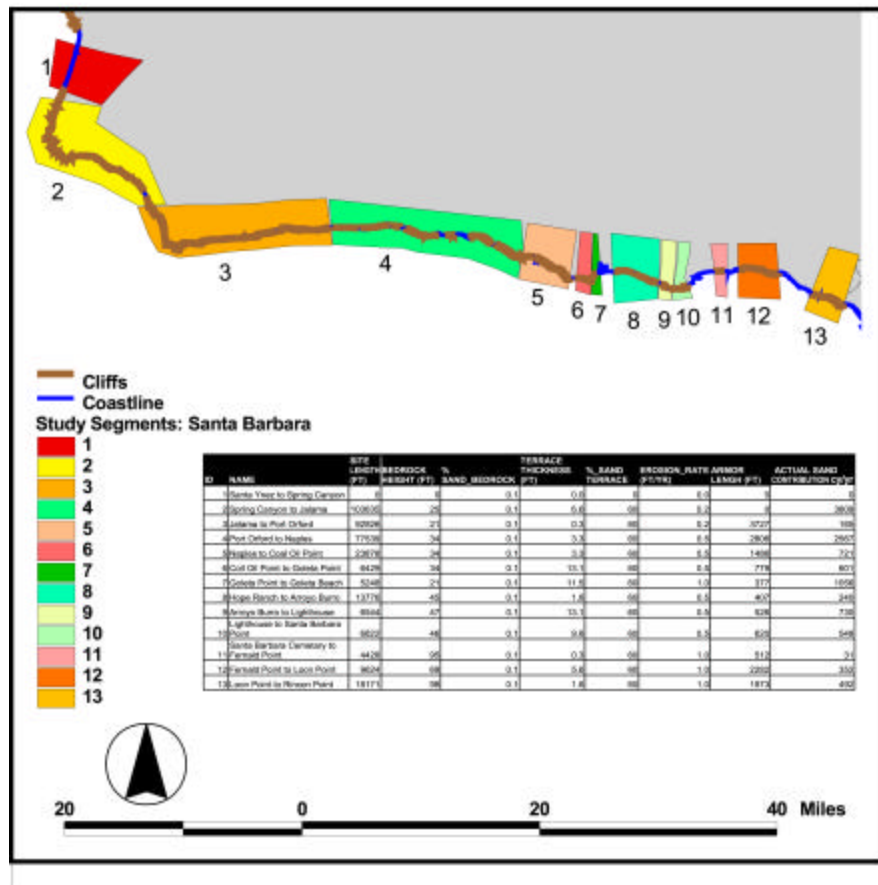


Figure 8.10 The Santa Barbara Littoral Cell showing individual segments used in sand contribution calculations

The Santa Maria River mouth was selected as the upcoast boundary for the Santa Barbara littoral cell. The large dune fields north of the river mouth suggest that most of the upcoast littoral sand is lost to inland sources at this location. There are two major rivers that deliver sediment to the

coast north of Pt. Conception. Willis (Section 7.1, this study) calculates that the Santa Maria River produces $\sim 260,000 \text{ yds}^3/\text{yr}$ of sand and the Santa Ynez River produces about $347,000 \text{ yds}^3/\text{yr}$. While there are no submarine canyons to serve as sinks upcoast from Pt. Conception, the littoral budget analysis carried out by Bowen and Inman (1966) calculated, using field observations and reasonable assumptions, that $\sim 106,000 \text{ yds}^3/\text{yr}$ of sand were lost to the extensive dune fields south of the Santa Maria River (Figure 8.11). The average annual sand discharge for the Santa Maria River, San Antonio Creek and the Santa Ynez River totals $\sim 668,000 \text{ yds}^3$ (Section 7.1, this study). Losses to the dunes remove $\sim 106,000 \text{ yds}^3/\text{yr}$ leaving a net of $562,000 \text{ yds}^3/\text{yr}$ of littoral sand in transit towards Pt. Conception.

It has long been debated (USACOE, 1955; Azmon, 1960; Bowen and Inman, 1966; Duane and Judge, 1969; Judge 1970; Pollard, 1979; Diener, 2000) whether sand from the Santa Ynez and Santa Maria rivers moves around Point Conception to contribute sand to the Santa Barbara littoral cell, or whether Pt. Conception forms a littoral drift barrier.



Plate 8.15 Cliffs north of Goleta Point, Santa Barbara County

In 1952, Trask examined the heavy minerals of beaches and streams between Monterey Bay and Santa Barbara and also investigated the question of whether sand moves around promontories along the California shoreline. Trask (1955) studied the Pt. Conception area as well as several other promontories in Southern California. The initial evidence he encountered that indicated that littoral sand does move around Pt. Conception was the presence of the mineral augite in the beach sands at Santa Barbara. While the augite concentration was only 3%, this percentage increased up coast to 10% at Pt. Conception and 50% north of Pt. Conception near the Santa Maria River. Stream sediment samples taken between Santa Barbara and Pt. Conception contained no augite, and Trask concluded that the cliffs along this coast (Plate 8.15) were not

eroding at a rapid enough rate to provide the 1000 yds³/day (~760 m³/day), on average, of sand that was moving alongshore. He also found that the cliffs contained no augite. A combination of beach and nearshore profiles, diver observations and sediment analyses were used to conclude that the sand on the beaches of Santa Barbara was being transported from north of Pt. Conception and then eastward alongshore to Santa Barbara. Trask found that active bypassing of the point occurs in a zone out to a depth of 33 ft (10m) and that some movement also takes place to a depth of 66 ft (20m).

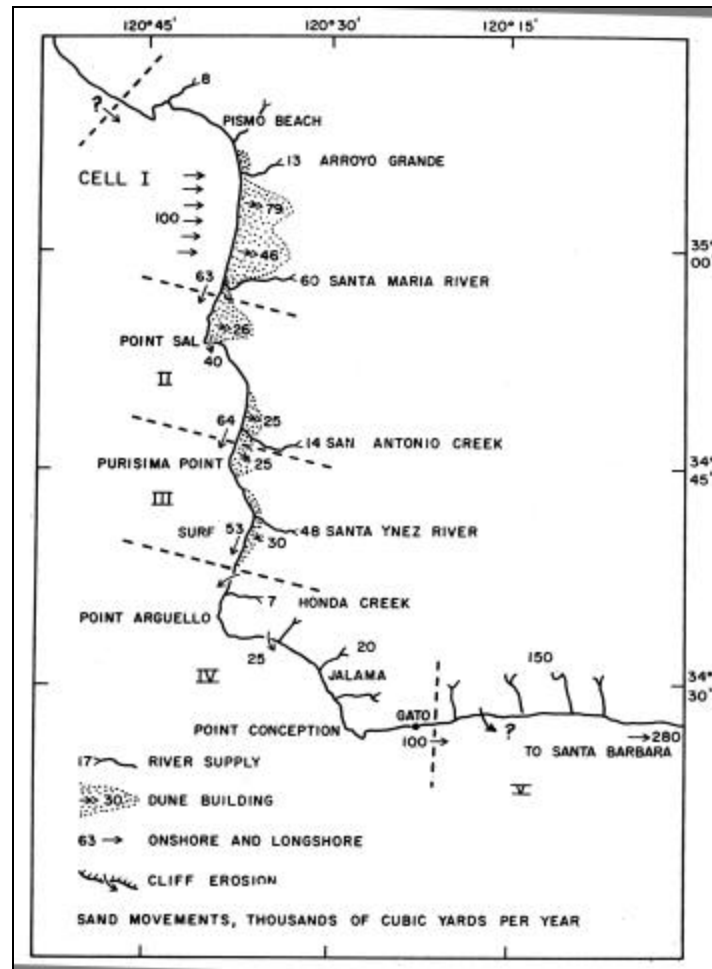


Figure 8.11 Sand budget for the Santa Barbara Littoral Cell (Bowen and Inman, 1966)

Studying heavy mineral assemblages in beach and offshore samples between Surf (north of Pt. Conception) and the Mexican border, Azmon (1960) also found greater amounts of augite north of Pt. Conception than east of it. On this basis, he concluded that the Point acts as at least a partial barrier to sediment movement. The generalized littoral budget developed by Bowen and Inman (1966) for the Pt. Arguello to Santa Barbara area also indicates that sand moves downcoast and around Pt. Conception and then continues to Santa Barbara (Figure 8.11). Judge (1970) concluded, based on sand tracer experiments in the vicinity of Pt. Arguello and Pt.

Conception, and from other evidence, that while this headland complex may act as a partial barrier, some sand does in fact move south and east around Pt. Conception.

Table 8.3 Is Pt. Conception a sediment barrier?

Researcher	Year	Method	Conclusion: Is sand moving around Point Conception?
Trask	1952	Heavy Mineral Tracer	Yes: Point Conception is a partial barrier, but sand is moving around it.
Azmon	1960	Heavy Mineral Tracer	Yes: Point Conception is a partial barrier, but sand is moving around it.
Bowen and Inman	1962	Sediment Budget	Yes: Point Conception is a partial barrier, but sand is moving around it.
Judge	1970	Sand Tracer	Yes: Point Conception is a partial barrier, but sand is moving around it.
Diener	2000	Sediment Budget	No

More recently, Diener (2000) studied the input of sand to the Santa Barbara littoral cell from the coastal bluffs between Pt. Conception and the Santa Barbara harbor and assessed the possibility that sediment travels around Pt. Conception. He used estimates of the annual volume of littoral sand entering the Santa Barbara harbor (Johnson, 1953) and estimates of stream and gully sediment input between Pt. Conception and Santa Barbara from Bowen and Inman (1966), combined with calculations of sediment input from the sea cliffs, to conclude that the cliffs provided the material needed to balance the littoral budget. Diener's conclusions, however, and the littoral budget he developed were evaluated carefully because they are in disagreement with previous research and budgets that concluded that sand is contributed to the Santa Barbara Cell by the area north of Pt. Conception (Table 8.3). Diener's calculations and littoral budget numbers are analyzed below.

Littoral transport at the Santa Barbara Harbor. Because the Santa Barbara breakwater (Plate 8.16) essentially serves as a complete trap for littoral transport at this point in the cell, the yearly dredging numbers from the harbor should provide a good measurement of annual littoral drift rates. Diener used a value from 1953 of 280,000 yds³/yr (212,000 m³/yr; Johnson, 1953) for the littoral transport rate. Average annual dredging values in recent years, however, which are more representative of present conditions, indicate a higher value. For the last 15 years (1986-2001), the annual dredging rate has averaged 357,000 yds³/yr (270,000 m³/yr; Myerson, 2001).



Plate 8.16 Santa Barbara breakwater and sand spit

Stream contributions between Pt. Conception and Santa Barbara: In Bowen and Inman's (1966) littoral budget for the Central California coast between Pismo Beach and Santa Barbara, they determined sand inputs and outputs. Based on sediment yield estimates from Johnson (1959), who used the Einstein bed load formula, Bowen and Inman estimate an annual contribution for the Santa Ynez River, and state that "*the series of small creeks between Pt. Arguello and Santa Barbara should have the same yield as the Santa Ynez River before flood control, some 700 yds³/mi²/yr.*" In their budget, they presumably take the total drainage area for these small watersheds and, using this estimated value, arrive at a value for stream contribution between Pt. Conception and Santa Barbara of 150,000 yds³/yr. Diener (2000), does not discuss or qualify the nature of these estimates, but uses the value (which is mistakenly reported as 170,000 yds³/yr) in his budget. Willis (Section 7.1, this report), using updated stream flow, sediment discharge and reservoir filling data, has recently recalculated the input of littoral sediment from the Santa Maria River, the Santa Ynez River, San Antonio Creek and also the streams draining the Santa Ynez Mountains between Pt. Conception and Santa Barbara to arrive at a total of 864,000 yds³/yr from fluvial sources along this coastal segment.

Cliff contributions from Pt. Conception to Santa Barbara: Utilizing the Santa Barbara harbor dredging numbers published by Johnson in 1953 (280,000 yds³/yr) and subtracting 170,000 yds³/yr (130,000 m³/yr) as an estimate of sand contributed from the upcoast streams, Diener (2000) reasoned that "*if the combined inputs from streams and gullies, and from bluff erosion, balances the 280,000 yds³ (Johnson, 1953) of sand estimated to enter the harbor annually, it can be assumed that sand is not entering from any other source*". Diener then measured the area of

the coastal bluff frontage between Pt. Conception and Santa Barbara harbor, determined bluff erosion rates for individual segments using USGS topographic sheets and recent aerial photos, and calculated the percentage of sand in the bluff materials in order to derive an annual sand volume contribution to the beaches of 106,000 yds³/yr. Combining the fluvial input of 170,000 yds³ and the calculated bluff erosion input of 106,000 yds³ produced a total yield of 276,000 yds³/yr, or nearly the same value quoted from Johnson (1953) for sand transport at the Santa Barbara harbor. There are concerns, however, with the sand percentages reported for the bluff materials and also with the methods used for determining bluff erosion rates, which significantly affect the importance of bluff erosion along this stretch of coast to the littoral budget.

Sand content of the bluff materials

The cliffs between Pt. Conception and the Santa Barbara harbor are 10-100 feet (3 – 30 m) in height and are cut into an uplifted marine terrace (Plate 8.17). The sea cliffs expose a basal bedrock unit (either the Monterey Shale, which is a Miocene marine shale, or the Sisquoc Formation, a diatomaceous silty shale) and an overlying sequence of unconsolidated marine terrace deposits and soils, ranging in thickness from 6 to 52 feet (2 to 16 m). Diener collected sediment samples from 32 different sites between Pt. Conception and Santa Barbara and reported *“the percentage of bluff material that was sand-sized was determined by sieve analysis for each. Each percentage was determined from a combination of each formation taken within the study area”*. Diener reported that the average sand content was 34.1% for the Monterey shale, 21.9% for the Sisquoc Formation, and 62% for the terrace deposits. These values were then combined with the area and erosion rate determined for each segment of bluff to provide a total sand contribution for the entire length of the bluff.



Plate 8.17 Eroding bluffs between Goleta Point and Coal Oil Point

Due to the high sand contents reported by Diener for two shale formations, we re-sampled the Monterey, Sisquoc and terrace deposits as part of this investigation. After attempting to break down the shale by a combination of hydrogen peroxide and some grinding, which still left large shale fragments, we put ~50 to 100 grams of the broken-up shale samples into a rock tumbler with an equal amount of beach sand and water, in order to simulate the abrasion process that goes on in the surf zone. We tumbled the samples for 12 to 24 hours and then washed the sediment through a 0.062 mm sieve to determine the amount of sand-size material remaining after subtracting the weight of the beach sand added for abrasion. In some cases, where the shale was very hard, there were still some larger fragments remaining (coarser than 1 mm). The weight of the shale fragments remaining was subtracted from the initial sample weight, and then the amount of sand that was derived from the bedrock or terrace sample breakdown was then converted to a percentage of littoral-size material.

While there may have been, on average, 34.1% of the ground-up shale that remained on a 0.062 mm (sand-size) sieve in Diener's grain size analysis, we believe that this was most probably shale fragments that would be broken down into clay and dispersed quickly in the surf zone. No littoral-size material resulted from the breakdown and analysis of any of the eight samples we collected from the Monterey Shale and Sisquoc Formation making up the bluffs between Goleta and Jalama, just north of Pt. Conception (Table 8.2). Thus, we conclude that the bedrock material exposed in the cliffs between Pt. Conception and Santa Barbara is not a significant contributor to the sand budget in this cell. One bedrock sample from the current study did contain 16% littoral-size material. It was collected from Pt. Santa Barbara, near the Santa Barbara Harbor. This point consists of the Santa Barbara formation, which does contain sand but has only a very limited coastal outcrop area.

Diener also determined the sand contribution from the terrace deposits, which averaged 62% sand. Terrace samples were sampled and analyzed in this study from six locations extending from Jalama to Rincon Point, north of Ventura. With the exception of one anomalous very fine-grained terrace sample from the Isla Vista area, the terrace samples averaged 60% littoral-size sand, very comparable to the value Diener obtained. These samples were unconsolidated, however, so no significant disaggregation was required.

Erosion rates and sand contributions

Unfortunately, erosion rates for the bluffs in the Santa Barbara cell are not well documented (Figure 8.2). In *Living with the California Coast* (Griggs and Savoy, 1985), sixteen erosion rates throughout the length of the cell were reported. These rates range from 3 inches (7.6 cm) per year in the Jalama area to 12 inches (30.5 cm) per year near Rincon, overall a relatively narrow range (Table 8.2).

Using the methods outlined in Section 8.4.1 of this report, the overall “natural” sand contribution from bluff erosion for the entire Santa Barbara Littoral Cell is estimated to be 14,000 yds³/yr (10,700 m³/yr) (Table 8.2).

In 1989, Noble Consultants estimated that the coastal bluffs from Coal Oil Point (Goleta) to Point Mugu contributed approximately 10,000-15,000 yds³/yr (8,000-11,000 m³/yr) of sand to the shoreline. Sea cliffs along this stretch of coastline range in height from 10 to 100 feet (3 to 30 m), and consist predominantly of Monterey and Sisquoc Formations capped by 2 to 20 feet unconsolidated terrace deposits. Noble Consultants based the contribution of sand-sized material emanating from sea cliffs in the Santa Barbara littoral cell on work done by Pollard (1979) on the cliffs west of the Santa Barbara Harbor. Pollard assumed a uniform bluff retreat rate of 0.5-1 ft/yr, an average cliff height of 40 ft, and a 60% sand contribution from the cliffs to end up with 73,000 yds³/yr (95,000m³/yr) of beach size material coming out of the sea cliffs from Point Conception to Goleta Point. Noble Consultants developed a unit source volume rate by dividing Pollard’s estimated quantity by the number of applicable shoreline miles. This leads to a volume of 2,000 cubic yards of sand, per mile of beach, emanating from bluff erosion; thus, they assume that the cliffs between Goleta Point and Santa Barbara harbor produce another 10,000-15,000 yds³/yr of sand.

The segment of the Santa Barbara cell analyzed by Noble Consultants does not include the coast from Coal Oil Point to Spring Canyon, north of Pt. Conception; however when they added their 10,000-15,000 yds³/yr of sand to the cliff contribution calculated by Pollard (73,000 yds³/yr) from Point Conception to Goleta Point, the estimated value of cliff input is considerably higher than our calculations (Noble: 90,000 yds³/yr; this study: 14,000 yds³/yr) for the Santa Barbara littoral cell. The discrepancy between the Noble Consultants (1989)/ Pollard (1979) study and the results from the present study is due to the percent of beach-size material found in bedrock and terrace materials; Pollard and thus Noble Consultants assume a uniform contribution of 60% sand composition of cliff material, while we found a 0.1% sand composition in the bedrock and 66% sand composition in the relatively thin overlying terrace material.



Plate 8.18 Bluff erosion in Isla Vista, Santa Barbara County

Extent of coastal protection structures and impact on sand production from cliff erosion

Bluff failures have been devastating to many cliff-top developments in the Santa Barbara Cell, including Channel Drive, Del Playa, El Camino, Cliff Drive, and Isla Vista (Plate 8.18). As with the Oceanside Littoral Cell and most of Southern California, the typical response in the past to the threat of bluff failure has been the construction of hard protection structures (Figures 8.12 and 8.13). Sea walls, rip-rap or other armoring, including breakwaters, now protect 44% or 33 miles (52.8 km) of the coastline of the Santa Barbara cell. Only 11 miles of this armoring is protecting sea cliffs, however; the remaining armor is protecting beaches and harbors and is not impacting the natural sand supply to the coast from cliff erosion. The shore-parallel armor is estimated to be preventing approximately 2,700 yds³/yr (2,000 m³/yr) of sand from ending up on the beaches of the cell (Table 8.2). This represents 19% of the original or “natural” contribution to the littoral budget from bluff erosion.

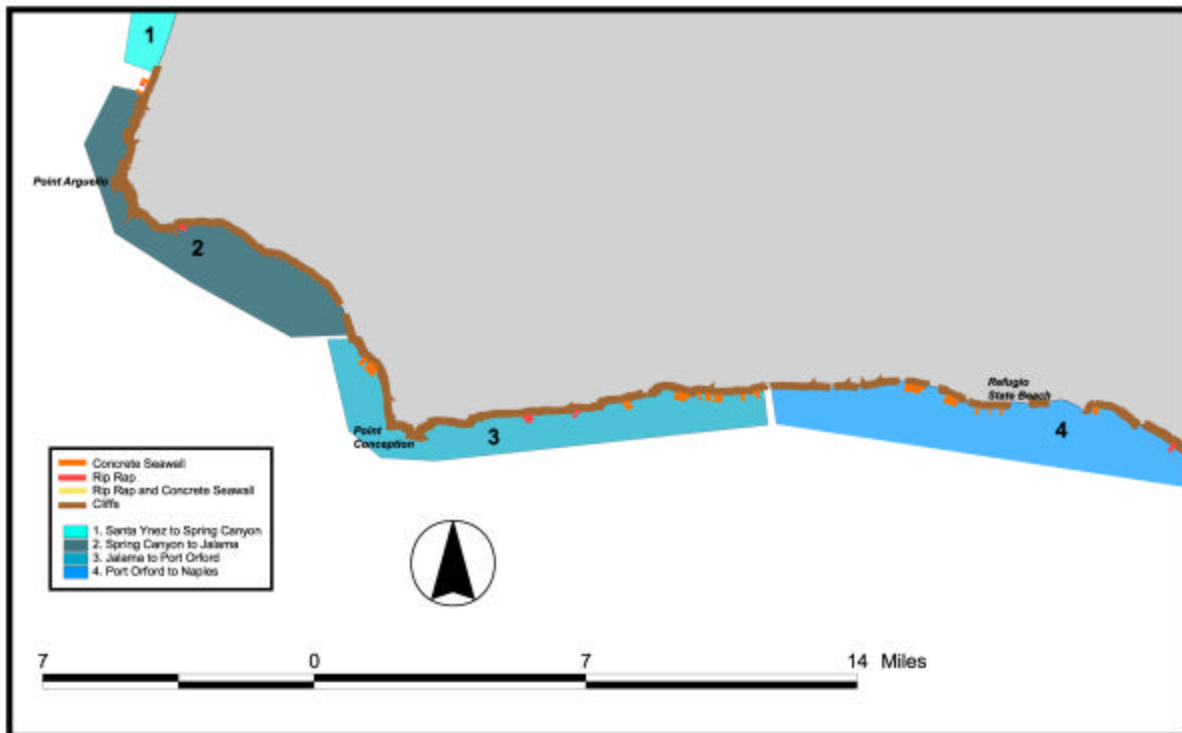


Figure 8.12 Armor in the Santa Barbara Cell-Spring Canyon to Naples

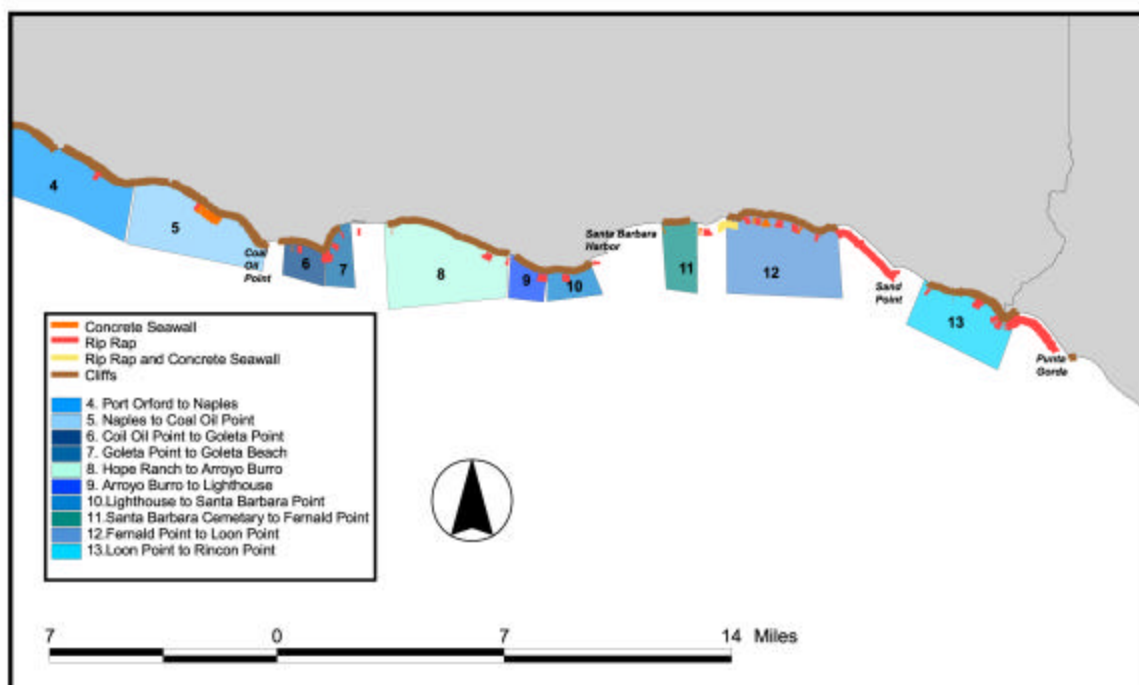


Figure 8.13 Armor in the Santa Barbara Cell-Naples to Punta Gorda

Sediment inputs to the Santa Barbara Cell and human impacts

It is important to evaluate the significance of the reduction of littoral sand through bluff armoring to the entire budget of the Santa Barbara littoral cell. There have long been concerns with both bluff erosion and perceived beach erosion in the down coast portion of the cell. The construction of the harbors at Santa Barbara, Ventura and Channel Islands as well as dams on the Ventura and Santa Clara rivers and the armoring of the bluff have all affected the overall sand budget.

We have updated the sand inputs for the Santa Barbara cell based on the most recent calculations or measurements of river discharge, cliff erosion and harbor dredging (Figure 8.14; gully erosion is not a significant source of beach sediment in the Santa Barbara cell). The present-day average annual sand input from the streams into the cell total $\sim 2,167,000 \text{ yds}^3/\text{yr}$, and include the following (Section 7.1, this report):

- Santa Maria River: $\sim 261,000 \text{ yds}^3$
- San Antonio Creek: $\sim 60,000 \text{ yds}^3$
- Santa Ynez River: $\sim 347,000 \text{ yds}^3$
- Streams between Pt. Conception and Santa Barbara: $\sim 196,000 \text{ yds}^3$
- Ventura River: $\sim 103,000 \text{ yds}^3$
- Santa Clara River: $\sim 1,200,000 \text{ yds}^3$

Total natural input from bluff erosion was $\sim 14,000 \text{ yds}^3/\text{yr}$, which has been reduced to $\sim 11,300 \text{ yds}^3/\text{yr}$ due to construction of coastal armoring structures.

Littoral sand inputs to the Santa Barbara cell at present total $2,167,000 \text{ yds}^3/\text{yr}$, of which stream input contributes 99.5% with bluff erosion contributing the remaining 0.5%. Prior to armoring and dam construction, the cliffs contributed 0.4% of the entire sand supply to the cell. Bluff armoring has reduced the total sand input to the Santa Barbara cell by $2,716 \text{ yd}^3/\text{yr}$ or 0.1% of the total budget.

Estimates of littoral sand contribution to the cell can be evaluated by looking at the sand budget at a specific location within the cell, such as the Santa Barbara harbor (Plate 8.16). Average annual present-day upcoast sand inputs include $864,000 \text{ yds}^3$ of stream input and $10,400 \text{ yds}^3$ of bluff input, for a total of $874,400 \text{ yds}^3/\text{yr}$. Approximately $106,000 \text{ yds}^3/\text{yr}$ of sand are lost to the dunes north of Pt. Conception every year, resulting in an annual littoral drift volume of $768,400 \text{ yds}^3$ up coast of the harbor. The average annual maintenance dredging volume at the Santa Barbara harbor ($357,000 \text{ yds}^3$; Myerson, 2001), however, is $411,400 \text{ yds}^3$ lower than the sediment input volume. This is a very large volume discrepancy, which could be accounted for by a combination of 1) significant volumes of littoral sand not being transported around Pt. Conception, as others have concluded; 2) significant volumes of sand bypassing the Santa

Barbara harbor and therefore not being included in the annual dredging volumes; and 3) uncertainties in the calculations of the sediment inputs from the streams in the cell.

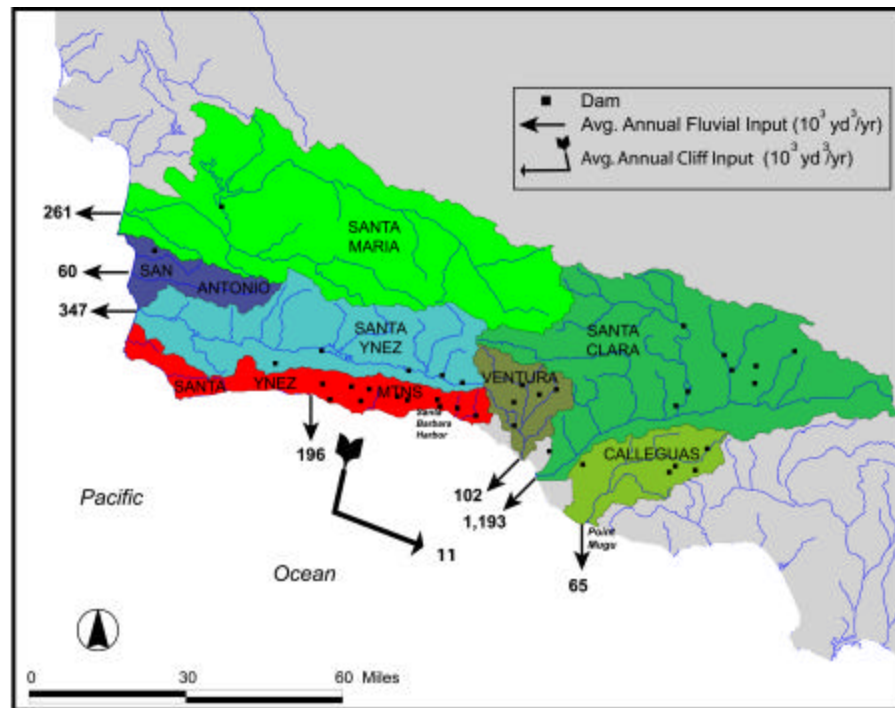


Figure 8.14 Sediment Inputs to the Santa Barbara Littoral Cell

8.7 Discussion

The Santa Barbara and Oceanside littoral cells were selected for detailed sediment input analysis because their beaches are intensively-used recreational areas and there have been concerns expressed in recent years regarding narrowing or erosion of the beaches. In both cells, coastal bluff development is both dense and threatened by bluff erosion, leading to the wide use of armor to protect the bluffs. The objectives of this portion of the study were to assess the degree to which coastal bluff protection structures have reduced the supply of sand to these littoral cells and to make any appropriate recommendations for future action or policy that might lead to an increase in the natural sediment supply to the coast.

Santa Barbara Cell: The Santa Barbara littoral cell is 144 miles in length and cliffs make up 78 miles or 54% of the coastline of the cell. Most of the cliffs have been cut into uplifted marine terraces by wave action (Plate 8.15). In order to reduce bluff erosion and protect coastal development, 11 miles or 14% of the cliffs in the cell have now been armored. A sediment input analysis for the entire cell indicates that, prior to construction of any dams, streams contributed approximately 3,642,773 yds³/yr on average; this has now been reduced ~ 40.5% to 2,167,000 yds³/yr (Table 8.4; Section 7.2, this report). This represents an average annual reduction of

~1,475,773 yds³/yr for the entire cell. Coastal bluff erosion naturally provided ~ 14,000 yds³/yr and this has been reduced 19.3% to 11,300 yds³/yr through the emplacement of coastal armoring. This represents a reduction of 2,700 yds³/yr.

Table 8.4 Sediment Inputs to the Oceanside and Santa Barbara Littoral Cells

Oceanside Littoral Cell			
Inputs	Natural (cy/yr)	Actual (cy/yr)	Reduction (cy/yr)
Rivers	286,500 44.7%	132,500 27.9%	154,000 53.8%
Bluff Erosion	67,300 10.5%	54,900 11.6%	12,400 18.4%
Gullies/Terraces	287,000 44.8%	287,000 60.5%	0 0.0%
Total Littoral Input	640,800 100.0%	474,400 100.0%	166,400 26.0%
Santa Barbara Littoral Cell			
Inputs	Natural (cy/yr)	Actual (cy/yr)	Reduction (cy/yr)
Rivers	3,642,773 99.6%	2,167,000 99.5%	1,475,773 40.5%
Bluff Erosion	14,028 0.4%	11,312 0.5%	2,716 19.3%
Total Littoral Input	3,656,801 100.0%	2,178,312 100.0%	1,478,489 40.4%

Overall, of the historic or natural littoral sediment inputs to the Santa Barbara cell, streams contributed 99.6% of the sand, while bluff erosion contributed only 0.4% (Table 8.4; Figure 8.14). Today, bluffs contribute 0.5% of the total littoral sand and the effect of armoring the 11 miles of seacliffs in the cell has been a total reduction in the littoral sand supply of ~ 0.1%.

Oceanside Cell: The Oceanside Littoral Cell is about 48 miles in length and cliffs or bluffs make up 35 miles, or 73%, of the coastline. Throughout much of this cell, as with the Santa Barbara cell, the cliffs have been eroded into uplifted marine terraces that have been extensively developed (Plate 8.19). Seven miles, or 20%, of the bluffs of the cell have now been armored. A sand input analysis for the entire littoral cell indicates that streams historically provided ~286,500 yds³/yr, on average, and that dams have reduced this input to 132,500 yds³/yr (Section 7.2, this report). This represents an average annual reduction of ~ 154,000 yds³/yr. Bluff erosion prior to the emplacement of seawalls and rip-rap contributed an additional 67,300 yds³/yr (Tables 8.2 and 8.4) and this has been reduced to 54,900 yds³/yr due to bluff armoring. Thus, armoring has reduced the sand input to the cell by ~12,400 yds³/yr.

Previous research in this cell indicates that gully erosion and subaerial erosion of the uplifted marine terraces contribute $\sim 287,700 \text{ yds}^3/\text{yr}$, for a total natural sand input to the Oceanside cell of $\sim 640,800 \text{ yds}^3/\text{yr}$ (Table 8.4). Thus, bluff erosion historically contributed 10.5% of the sand to the Oceanside cell, streams contributed 44.7%, and gully erosion and upland terrace degradation made up the remaining 44.8%.



Plate 8.19 Blufftop development in the Leucadia area of the Oceanside Cell

The construction of dams has reduced stream input by $\sim 154,000 \text{ yds}^3/\text{yr}$, and the emplacement of armor now has reduced the sand input from bluff erosion by $\sim 12,400 \text{ yds}^3/\text{yr}$. Bluffs now contribute 11.6% of the total littoral sand to the cell and the effect of armoring seven miles of bluffs in the cell has been to reduce the total littoral budget by about 2%.

Recommendations for the Future

The construction of dams and coastal armor structures have reduced the total sand supply to the Santa Barbara and Oceanside littoral cells by an estimated 40.4% (1,478,489 yds³/yr) and 26.0% (166,400 yds³/yr), respectively. These are significant human modifications of large natural systems, although the long-term effects of these source reductions have not yet been quantified. While there is considerable anecdotal information, as well as observations and photographic records, about shoreline erosion and coastal storm damage in both cells, there are no long-term (50 years or more) documented or published records of systematic changes in beach width or volume. Long-term changes in beach width need to be quantified, evaluated and then compared to the calculated reductions in littoral sand supply to both cells in order to confirm the correlation between the two phenomena. Specifically, has the reduction in the calculated sand input from a particular stream or at a specific location in the cell produced a related long-term reduction in beach width or volume downdrift of that location?

Although the values calculated and included in this report for both historic or natural and present-day quantities of littoral sand supplied by streams, bluff erosion, and terrace and gully erosion are precise, it is important to keep in mind the uncertainties involved in determining these values. An analysis of the errors associated with the values used in this report is included in Appendix D.

Another important factor to consider in evaluating the values calculated for sand input from streams and the reduction in these values due to dam construction is the connectivity between the upstream gauging station or location where the sediment discharge was determined and the shoreline. Many of these streams cross broad alluvial valleys prior to arriving at the shoreline, and much of the sediment measured at upstream gauges may be deposited along these alluvial reaches before ever reaching coast. With some of the smaller streams, the sediments may be deposited in estuaries or lagoons at the mouths of streams. Most of the major rivers, however, do not empty into estuaries but discharge into the ocean. Nevertheless, the actual sediment loads calculated and their apparent reduction may not be reflected immediately on the shoreline and sediment delivery to the coast may be considerably less than what has been calculated using stream gauge data. Sediment storage in coastal lowlands is an area of investigation that needs to be undertaken to quantify these differences and determine the actual reduction in fluvial sand delivery at the coastline.

What is clear from Table 8.4 is that bluff erosion plays an insignificant role as a source of sand for the Santa Barbara littoral cell in particular. The total amount of sand supplied to the beaches by bluff erosion, whether under natural (historical) or actual (current) conditions, is less than 1% of the total littoral budget. This is due in large part to the low percentage of sand in most of the bluff materials and the relatively low historic rates of bluff retreat. The volume of sediment supplied by the streams draining and eroding the Transverse Ranges is very large, however,

although this volume has been reduced significantly by dam construction. Any plans or proposals to increase the natural sediment supply to the beaches of the Santa Barbara cell should focus on stream contributions, not the bluffs.

While streams contribute 99.5% of the littoral sand to the Santa Barbara cell, they contribute only 27.9% of the sand to the Oceanside cell. The remaining sand in the Oceanside cell comes from the erosion of the bluffs (11.6%), and from upland terrace erosion and gully enlargement (60.5%). Thus, bluff erosion is a significant contributor to this cell and future armoring proposals need to fully evaluate impacts on sand production, as is presently required by the California Coastal Commission through its *in lieu* sand mitigation fee program.

In the Santa Barbara cell, large volumes of sand are regularly dredged from the three major harbors in the cell: Santa Barbara, Ventura and Channel Islands. Because each of these harbors serves as a major littoral drift barrier, the annual or bi-annual dredging volumes should provide a reasonable indicator of long-term littoral drift rates at those points in the cell. While there are year-to-year variations in the dredging volumes, there has been no systematic reduction in the amount of sand removed each year from the harbors, strongly suggesting that there has not been a significant or regular reduction in the volume of littoral sand moving through the cell over the past 30 to 40 years. We have not collected dredging information for the Oceanside cell, so we have not assessed the issue of change in littoral sand volumes in this area.

It is recommended that a detailed study of historic beach widths and volumes within all littoral cells be carried out in order to document the extent to which a regular or systematic reduction in width has taken place, and then to determine how this reduction relates spatially and/or temporally to the reduction of natural sediment supply. Littoral drift estimates from harbor dredging rates will provide an important cross-check on any historic changes in beach width or volume. Without question, significant reductions in sand transport by the streams of both cells have taken place. Whether or not this has been reflected at the shoreline as changes in beach width, and whether the reduction has directly affected just portions of the cell or the entire cell, are issues yet to be resolved.

Selective dam removal and bypassing appear to be the approaches that have the potential to significantly increase natural sand supply and to return the littoral drift systems to their natural condition. Dams have caused the greatest reductions in the supply of sand to the coast and removal of those that are no longer serving any significant function, and bypassing of sediment around dams that are functional but impound significant volumes of sediment, should be vigorously pursued.

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8.9 GLOSSARY

Bluff: A high bank or bold headland, presenting a precipitous front; a steep cliff.

Channelized Stream: A stream whose channel has been straightened and / or deepened to permit water to flow faster.

Coastline: The general boundary between land and water, especially, the water of a sea or ocean.

Fluvial: Of or pertaining to a river; growing or living in a stream or river, produced by the action of a stream or river.

Franciscan: A complex and heterogeneous assemblage of rocks exposed in the Coast Ranges and along the sea cliffs of California consisting of sandstone, shale, conglomerate, volcanic rocks, chert and limestone as well as metamorphic rocks including serpentine.

Geographic Information System (GIS): A computer system that records, stores, and analyzes information about the features that make up the earth's surface.

Littoral Cell: A segment of coastline that includes sand sources, alongshore transport or littoral drift, and then a sink or sinks for the sand; also known as a beach compartment.

Littoral Current: A coastal current caused by waves approaching and then breaking along the shoreline at an angle. It flows parallel to and near to the shore and is also known as a longshore current.

Littoral Cutoff Diameter: Lower-end size limit for material that will be carried in the littoral drift and deposited on a particular beach. Smaller material will remain in suspension until reaching a lower-energy environment when it will fall out of suspension.

Littoral Drift: Material (such as sand, gravel, and shell fragments) that is moved along the shore by a littoral or longshore current.

Marine Terrace: A wave-cut platform that has been exposed along a coastline by uplift, a lowering of sea level, or a combination of the two.

Revetment: An engineered rock structure consisting of filter cloth, smaller core stone, and then large cap stone which is designed to armor or protect a coastal bluff, dune, or development from wave attack.

- Rip-rap:** A structure consisting of large rocks stacked against a bluff, dune or beach in order to provide protection from wave attack.
- Runoff:** That portion of precipitation that flows over the land surface as slope wash and in stream channels.
- Sea cliff:** A cliff formed by wave action as well as subaerial processes.
- Shoreline:** The intersection of the sea or a lake with the shore or beach; it migrates with changes of the tide or of water level.
- Shore-Parallel Engineering Structure:** Any armor or protective structure that is constructed parallel to the coastline, such as a seawall or revetment.
- Terrace:** A relatively level bench or step-like surface breaking the continuity of a slope.
- Uplift:** A tectonic process that takes place at plate boundaries and elevates large areas of the earth's crust